USING VALUE-FOCUSED THINKING TO EVALUATE THE PRACTICALITY OF GROUND-SOURCE HEAT PUMPS AT MILITARY INSTALLATIONS

THESIS

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AFIT/GEM/ENS/05M-01

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AFIT/GEM/ENS/05M-01

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THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Engineering and Engineering Management

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March 2005

AFIT/GEM/ENS/05M-01

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AFIT/GEM/ENS/05M-01

Abstract

Because of potential cost and energy savings, military decision-makers may want to consider the use of energy-efficient heating, ventilating, and air-conditioning (HVAC) systems at their installations. Ground source heat pumps (GSHPs), in particular, show great promise because of their low energy requirements and low life-cycle costs. However, there currently exists no design guidance or established criteria for HVAC selection. Consequently, military decision-makers have no basis for comparing conventional HVAC systems and GSHPs.

The Value-Focused Thinking (VFT) methodology was used to create a multi-objective decision analysis model that measures the value of different HVAC systems. Consisting of five bottom-tier values and twelve measures, the model captures the Air Force's objectives regarding its selection of HVAC systems. Using data collected from three different Air Force bases, the model was used to evaluate four HVAC alternatives (three conventional and one GSHP alternative) at each location. Sensitivity analysis was also conducted to provide additional insight into the HVAC selection process. The results of this research indicate that GSHPs are a viable option and should be considered at military installations. Further, the results prove that the VFT model can be an effective decision analysis tool for HVAC selection.

Acknowledgments

I would like to express my sincere appreciation to my thesis advisor, Lt Col Jeffery Weir, for his guidance and support throughout the course of this thesis effort. His expertise and patience were greatly appreciated. I would like to thank Dr. Alfred Thal, who despite his busy schedule, volunteered to "fill in" as my thesis advisor during Lt Col Weir's deployment. I would also like to thank Lt Col England for taking the time to thoroughly review my thesis drafts.

Special thanks to Dr. Charles Fenno and the Civil Engineer and Services School for allowing me to use the Trace™ 700 software. Special thanks are also in order to Mr. Alvin Day for providing the inspiration for this research and helping build the model. Finally, I would like to thank God for giving me the opportunity to undertake this challenging and ultimately, rewarding experience.

Captain Jimmy J. Jeoun

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USING VALUE-FOCUSED THINKING TO EVALUATE THE PRACTICALITY OF GROUND-SOURCE HEAT PUMPS AT MILITARY INSTALLATIONS

I. Introduction

Background

Because of the increasing population and expanding economy of the United States, energy consumption has reached unprecedented levels. In 2002, the U.S. consumed 97.3 quadrillion British Thermal Units (BTUs) of energy, which is only exceeded by the record 98.9 quadrillion BTUs consumed in 2000 (DOE, 2003b). This accounts for over 23% of the world's energy consumption, despite the fact that the U.S. represents only 4.6% of the world's population (U.S. Census Bureau, 2003; U.S. Census Bureau, 2004a). Unfortunately, the growth rate of U.S. energy production has not matched the growth rate of U.S. energy consumption. Given that the U.S. population is projected to increase nearly 50% by 2050, the imbalance between energy supply and energy demand threatens to increase (U.S. Census Bureau, 2004b). If allowed to grow, this imbalance "will inevitably undermine our economy, our standard of living, and our national security" (Bush, 2001).

To help meet future energy needs, the development of renewable energy resources is essential. Renewable resources take advantage of naturally occurring sources of energy, such as the sun, wind and geothermal heat, and typically have less impact on the environment than conventional sources. In 2001, renewable resources made up only 6% of the total energy consumption in the U.S. (DOE, 2003b). As depicted in Figure 1,

biomass (wood, waste, and alcohol), hydroelectric power, geothermal, solar, and wind accounted for only 6 of the 97.3 quadrillion BTUs consumed in 2002. However, renewable energy resources are domestically abundant and have the potential to provide increased levels of electricity and fuel. Solar, wind, biomass, and geothermal heat, in particular, have the most potential for growth (Bush, 2001).

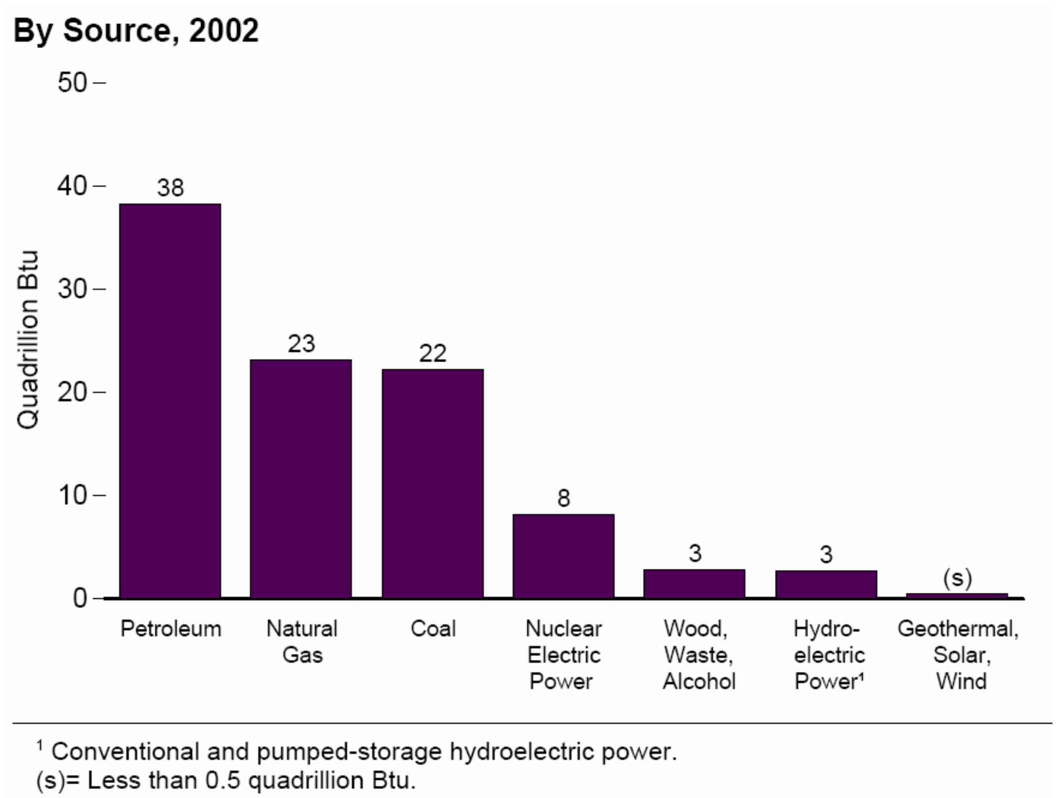


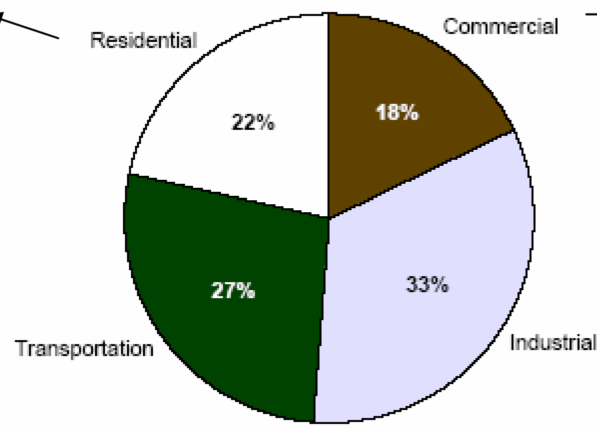
Figure 1. U.S. Energy Consumption by Source in 2002 (DOE, 2003b)

This research focuses on the energy consumption of heating, ventilating, and air-conditioning (HVAC) systems. In 2002, HVAC systems consumed 15.2 quadrillion BTUs of energy or roughly 15% of the total U.S. energy consumption (DOE, 2003b).

Further, a closer look at specific end-use sectors reveals that HVAC functions (i.e. space heating, space cooling, and water heating) account for the largest percentage of energy consumption in residential and commercial facilities (see Figure 2). Indeed, over 50% of the residential consumption and over 25% of the commercial consumption can be attributed to HVAC systems (DOE, 2003b).

End-Use Sector Shares of Total Consumption, 2002

Residential Breakdown	
Space Heating	30.54%
Space Cooling	10.14%
Water Heating	12.74%
Refrigeration	6.98%
Cooking	2.81%
Clothes Dryers	4.12%
Freezers	2.23%
Lighting	11.60%
Clothes Washers	0.50%
Dishwashers	0.38%
Color Televisions	1.88%
Personal Computers	1.04%
Furnace Fans	1.17%
Other Uses	13.84%



Commercial Breakdown	
Space Heating	11.18%
Space Cooling	7.75%
Water Heating	6.23%
Ventilation	3.01%
Cooking	2.04%
Lighting	20.35%
Refrigeration	3.68%
Office Equipment	8.26%
Other Uses	37.50%

Figure 2. U.S. Energy Consumption by Sector in 2002 (DOE, 2003b)

Given that the majority of facilities on Air Force installations are either commercial or residential facilities, the potential for substantial energy savings through the use of more energy-efficient HVAC systems is evident. Yet, the Air Force has no formal policy guidance to aid HVAC designers who may be interested in implementing more energy-efficient systems. Consequently, Air Force HVAC designers often rely solely on previous experience when designing HVAC systems and overlook systems that they have not been exposed to previously.

Ground-source heat pumps (GSHPs), in particular, have great potential for energy savings. GSHPs use the relatively constant temperature of the earth as a resource, transferring heat from the ground to a building in the winter and transferring heat from the building to the ground in the summer. According to the Environmental Protection Agency (EPA), GSHPs are the most energy-efficient and environmentally clean space-conditioning system. It is estimated that GSHPs can reduce electrical energy consumption by 63 to 72 percent over conventional air-conditioning systems, depending on the location (EPA, 1993). If installed nationwide, GSHPs could save several billion dollars annually in energy costs. Despite their prospective benefits, GSHPs account for less than one percent of the space-conditioning market because HVAC designers are unfamiliar with the technology, initial costs are high, and the HVAC industry has not promoted GSHPs (GAO, 1994).

Legislation

The need to increase energy efficiency in government facilities has been the topic of legislation for many years. By definition, energy efficiency is "the ability to use less energy to produce the same amount of lighting, heating, transportation, and other energy services" (Bush, 2001). The federal government has typically taken two approaches to promote energy efficiency: offering incentives for energy-efficient technologies and establishing energy reduction goals.

Business tax credits for renewable energy projects have been a part of federal legislation for over 25 years. The Energy Tax Act of 1978 (ETA) established 10 percent tax credits for commercial investments in solar, wind, geothermal, and ocean thermal

technologies (United States Congress, 1978). The Crude Oil Windfall Profits Tax Act of 1980 (WPT) increased the business tax credits established in the ETA to 15 percent and extended the credits until 1985 (United States Congress, 1980). The Energy Policy Act of 1992 (EPACT) provided, among many initiatives, a permanent 10 percent business tax credit for investments in solar and geothermal technologies. EPACT also established minimum energy efficiency standards for buildings, including a building's HVAC systems (United States Congress, 1992).

On June 8, 1999, President William J. Clinton issued Executive Order (EO) 13123, "Greening the Government Through Efficient Energy Management" (Clinton, 1999). Among its many provisions are mandates for life-cycle cost analysis, facility energy audits, energy management tools, and sustainable building design. In addition, the EO encourages government agencies to purchase power from renewable sources and increase its use of renewable energy through renewable energy projects. Perhaps most importantly, EO 13123 mandates a 30% reduction in energy consumption by 2005 and a 35% reduction by 2010, relative to 1985 consumption.

Problem Statement

Because of the potential cost and energy savings, military decision-makers may want to consider the use of ground source heat pumps at their installations. However, there exists no design guidance or established criteria for HVAC selection. Consequently, military decision-makers have no basis for comparing conventional HVAC systems and GSHPs.

Therefore, the purpose of this research is to develop a design tool that measures the value of different HVAC systems. In order to be useful, the tool must capture the Air Force's objectives and values regarding its HVAC systems. The design tool must also be highly adaptable, given the various locations and climate conditions of the Air Force's installations.

Research Objective and Investigative Questions

The objective of this research is to provide a multiple-objective decision analysis model that can be used by decision-makers to evaluate the practicality of installing GSHPs at military installations. The following investigative questions will be addressed.

1. Given the various design considerations of HVAC systems, what is the appropriate methodology for HVAC selection?

2. What does the Air Force value in terms of their HVAC systems?

3. How do GSHPs perform in differing regions of the country?

Significance

Although this model will be used to compare GSHPs with conventional HVAC systems, the true significance of this model will be as a design tool to select the best HVAC alternative for a given location. Since no established criteria for HVAC selection currently exists, this model will provide the basis for comparison between different systems. Given an objective approach, military decision-makers will be able to make informed and justifiable decisions regarding the selection of HVAC systems.

II. Literature Review

Overview

This chapter summarizes the fundamentals of ground-source heat pumps (GSHPs) and analyzes the differences between GSHPs and conventional heating, ventilating, and air-conditioning (HVAC) systems. It begins with a general overview of air-conditioning, followed by a description of the common characteristics of conventional HVAC systems. Next, the chapter provides a background of GSHPs and the different types of GSHP systems. The chapter continues with a discussion on the current HVAC selection methodology, which leads into the concept of decision theory. Finally, the chapter introduces value-focused thinking (VFT), the multiple-objective decision analysis technique used for this research. Specifically, the methodology of the VFT process and the rationale for using VFT for this model will be explored.

Air-Conditioning Basics

Because of its numerous benefits, air-conditioning has become an integral part of modern society. In the home or workplace, air-conditioning is used to create a comfortable environment, increasing the productivity and enjoyment of the building's occupants. Industry produces many commercial products faster and more economically because of the use of air-conditioning. Furthermore, air-conditioning is used to maintain strict environmental conditions for sensitive operations, such as medical procedures or scientific research (Howell, Sauer, and Coad, 1998).

Air-conditioning, though, cannot be provided without the consumption of energy. Prior to 1973, air-conditioning systems were designed with little regard to energy conservation. However, as energy costs have risen and concern for the negative impact of energy consumption has grown, air-conditioning designers have had to consider the energy efficiency of their systems. Consequently, air-conditioning systems have become more complex and diverse, as designers seek an optimal balance between energy efficiency and performance (Johnson, 2000). Indeed, "more than seventy percent of the commercial-industrial-institutional buildings recently built in the United States made use of energy conservation measures for heating and cooling" (Howell et al., 1998). The emphasis on energy efficiency has also increased the use of renewable energy in air-conditioning systems.

Although the term "air-conditioning" is sometimes linked only to the process of cooling, the modern definition of air-conditioning includes all aspects of HVAC. Specifically, air-conditioning comprises seven major functions: heating, cooling, humidifying, dehumidifying, cleaning, ventilating, and air movement (Johnson, 2000). The seven functions are described in Table 1.

Table 1. Air-Conditioning Functions (Johnson, 2000)

Function	Description
Heating	The process of adding thermal energy to the air for the purpose of raising or maintaining the temperature of the air
Cooling	The process of removing thermal energy from the air for the purpose of lowering or maintaining the temperature of the air
Humidifying	The process of adding water vapor to the air for the purpose of raising or maintaining the moisture content of the air
Dehumidifying	The process of removing water vapor from the air for the purpose of lowering or maintaining the moisture content of the air
Cleaning	contaminants from the air for the purpose of improving or maintaining the air quality
Ventilating	The process of exchanging air between the outdoors and the conditioned space for the purpose of diluting the gaseous contaminants in the air and improving or maintaining the air quality, composition and freshness
Air Movement	The process of moving air through conditioned spaces in the building for the purpose of achieving the proper ventilation and facilitating the thermal energy transfer, humidification, and cleaning processes

Of the seven functions, the heating and cooling functions are the most basic and commonly understood (Johnson, 2000). The heating function is fairly straightforward, requiring only the use of a heat source, such as the burning of a fuel. The processing of cooling, on the other hand, is complex and warrants a closer look. To produce cooling, a means of removing thermal energy is required; cooling does not occur naturally on its own. In most cases, refrigeration is used for cooling, and of the various forms of refrigeration, the vapor-compression cycle is the most common (Howell, et al., 1998). The vapor-compression cycle consists of four mechanical components and a refrigerant that is circulated in a closed loop through the components. Because of the closed loop, the refrigerant is separated from the medium (usually air or water) that is being cooled. The components of the vapor-compression refrigeration cycle are shown in Figure 3.

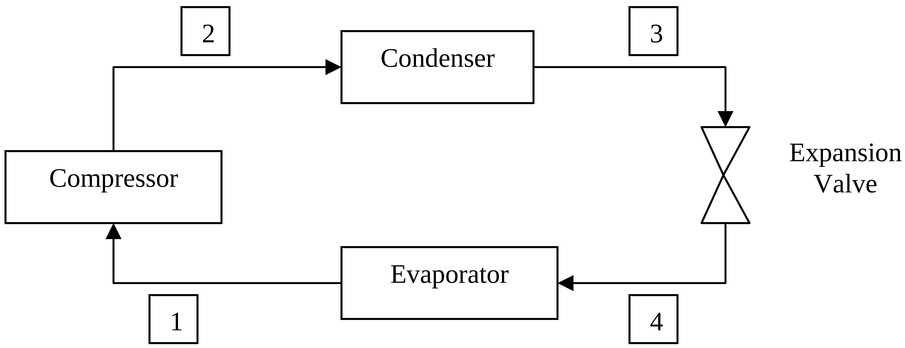


Figure 3. Vapor-Compression Refrigeration Cycle

The vapor-compression refrigeration cycle begins as the refrigerant enters the compressor as a hot, low-pressure vapor. The vapor is then compressed and leaves the compressor as a hot, high-pressure vapor. This high-pressure vapor then enters the condenser, where the heat is rejected or removed from the refrigerant. As a result, the refrigerant leaves the condenser as a warm, high-pressure liquid. The refrigerant is then sent through the expansion valve, which lowers the pressure of the refrigerant and results in a cold, low-pressure liquid. Finally, the low pressure liquid enters the evaporator and removes heat from its surroundings, producing the desired cooling effect of the refrigeration cycle. The process of removing heat from its surroundings causes the refrigerant to change from a cold, low-pressure liquid to a hot, low-pressure vapor and the process repeats (Cengel and Boles, 1994).

Characteristics of Conventional HVAC Systems

Given the varying configurations of HVAC systems, it can be difficult to define what makes a system conventional. For this research, a conventional HVAC system is a system that meets the following two characteristics. First, the system utilizes the refrigeration cycle, as described in the preceding section, for cooling. Second, because the vapor-compression cycle cannot be reversed, conventional HVAC systems must use separate, dedicated systems for heating. Figure 4 illustrates the most commonly used systems for both cooling and heating in commercial facilities.

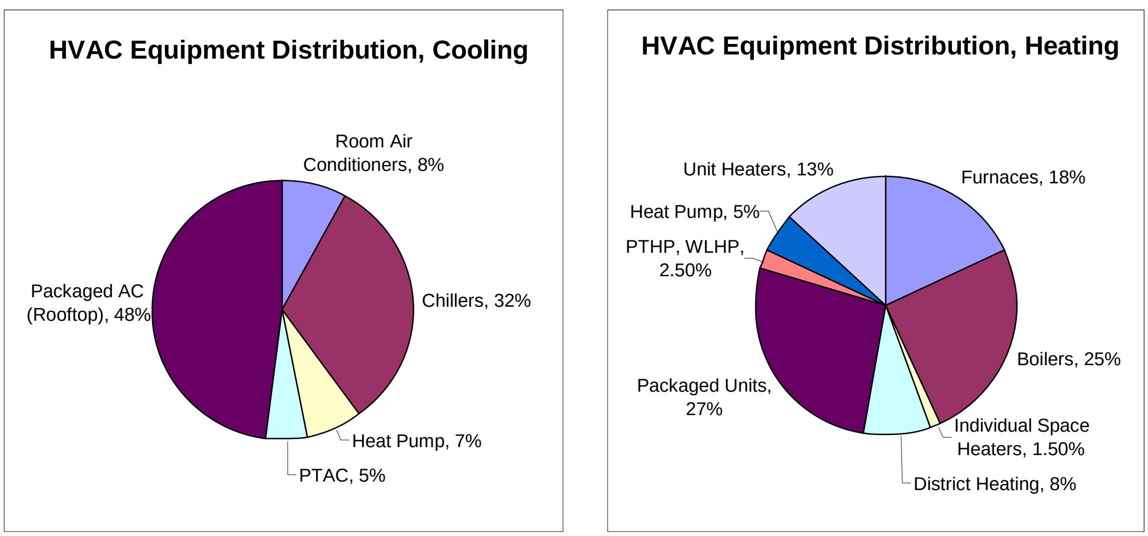


Figure 4. HVAC Equipment Distribution (Westphalen and Koszalinski, 2001)

For cooling, unitary systems (packaged air-conditioners, packaged terminal air conditioners (PTACs), and room air conditioners) account for 61% of the equipment used in commercial facilities (Westphalen and Koszalinski, 2001). Unitary systems are air-conditioning systems that include the components needed for cooling and/or heating in an

integrated enclosure. That is, the controls, fans, filters, and cooling components (cooling coils, piping, compressor, and condenser) are included in a single package. Unitary systems are designed to be installed either directly in the conditioned space or adjacent to the conditioned space. As a result, they reduce or eliminate the need for distribution equipment such as air handlers or ductwork. Unitary systems are advantageous when low initial cost and simplified installation are preferred. By convention, unitary systems that are designed for commercial applications are called packaged units. Appropriately, a packaged unit designed to be installed on a roof is called a rooftop unit. Room air-conditioners, or window air-conditioners, are unitary systems that are designed for mounting in a window. PTACs are unitary systems designed to be mounted through a wall (Howell, et al., 1998).

Chillers, which account for 32% of the equipment used in commercial facilities, are a basic component of central systems (Westphalen and Kozalinski, 2001). Unlike unitary equipment, central systems are located outside the conditioned space in a dedicated mechanical room or service area. Thus, central systems provide cooling by distributing conditioned air to the conditioned space. As depicted in Figure 5, the mechanical components of a basic central system typically include an air-handling unit (AHU), chiller, and cooling tower. The AHU distributes air to the conditioned space(s) through a system of fans and ductwork. Inside the AHU, coils are used to cool air under forced convection. Usually, chilled water is the cooling medium within the coils (Howell, et al., 1998). The chilled water is circulated in a closed loop to a chiller, which uses the vapor-compression cycle (compressor, condenser, evaporator, expansion valve, and a sealed refrigerant) to remove the building heat from the chilled water (Haines and

Wilson, 2003). The building heat is then dissipated into the atmosphere through the use of a cooling tower or air-cooled condenser. Systems that use cooling towers to reject the building's heat are known as water-cooled chillers, while systems that use ambient air to reject the building's heat are known as air-cooled chillers (Westphalen and Kozalinski, 2001). Among conventional HVAC systems, chiller systems are usually the most energy efficient (Kavanaugh and Rafferty, 1997).

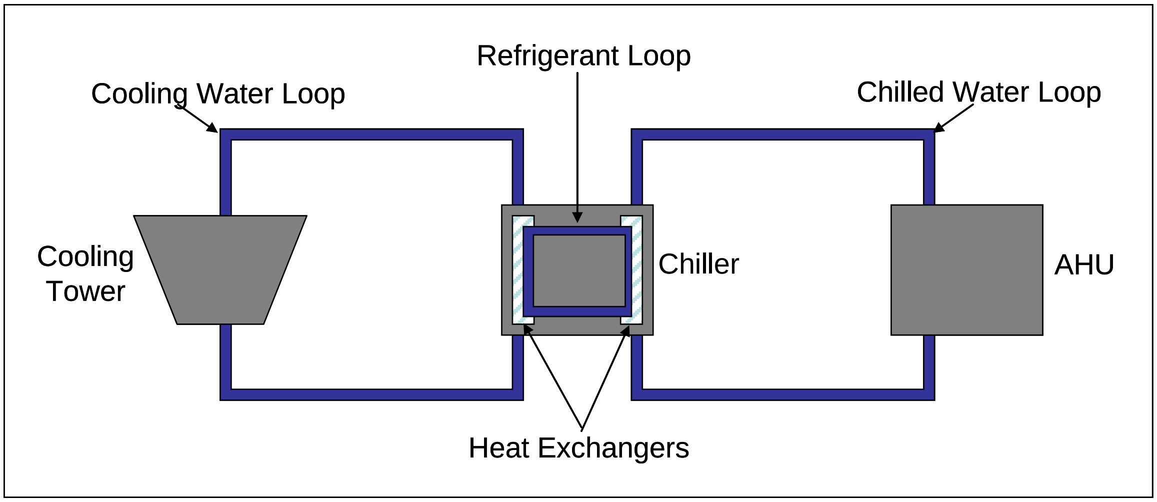


Figure 5. Typical Central System Components

Heat pumps account for the final 7% of the cooling equipment used in commercial facilities (Westphalen and Kozalinski, 2001). Heat pumps are air-conditioning systems that use the vapor-compression cycle to take heat from one source and transfer it to another location (Howell, et al., 1998). Unlike other HVAC systems, the heat pump's refrigeration cycle can be reversed. Thus, heat pumps use the same mechanical components to provide both heating and cooling.

In terms of heating, furnaces, boilers, and packaged units account for 72% of the equipment used in commercial facilities (Westphalen and Koszalinski, 2001). These heating systems normally use coal, oil, electricity, gas, or waste material as fuel (McQuiston and Parker, 1988). Unit heaters, heat pumps, packaged terminal heat pumps (PTHPs), water-loop heat pumps (WLHPs), individual space heaters, and district heating account for the final 28% of the heating equipment used in commercial facilities (Westphalen and Koszalinski, 2001).

Ground Source Heat Pump (GSHP) Overview

Ground-source heat pumps (GSHPs) are space-conditioning systems that use the relatively constant temperature of the ground to provide heating, cooling, and hot water. They are often referred to as ground-coupled heat pumps or geothermal heat pumps. Although the GSHP technology has existed for more than 40 years, it has only been utilized for commercial applications since the 1970s (Vukovic, 1996). There are a number of different GSHP technologies, but all GSHPs work by taking advantage of the thermodynamic properties of the shallow earth. A few feet below the surface, ground temperatures stay relatively constant throughout the year. As depicted in Figure 6, the temperature of the ground varies by less than ±10 degrees at a depth of 12 feet or lower (DOE, 2003a). Consequently, GSHPs are able to use the ground as a heat source during the winter and a heat sink in the summer.

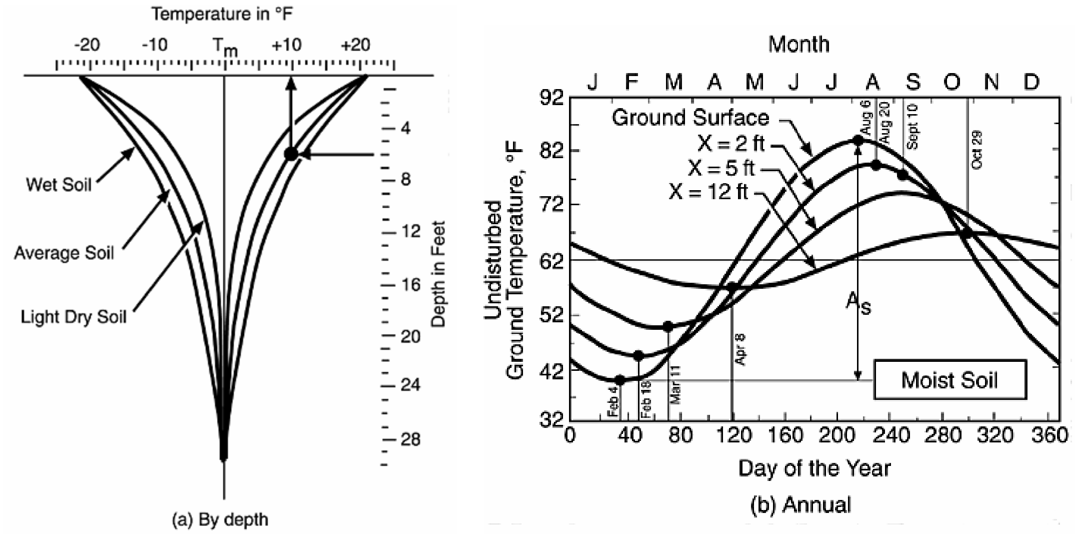


Figure 6. Soil Temperature Variation (DOE, 2003a)

It is important to note that the mean ground temperature is not only fairly constant, but also near the preferred temperatures for building interiors (see Figure 7). Thus, GSHPs have a relatively low temperature difference to overcome. This translates into greater operating efficiency and lower heating and cooling costs for GSHPs when compared to conventional HVAC systems. For instance, consider the following hypothetical example. According to Figure 7, Ohio has a mean earth temperature of approximately 53 degrees Fahrenheit. If the desired indoor temperature during the winter is 72 degrees, a GSHP system would have to overcome 19 degrees to meet the desired temperature. Since the design winter temperature in Ohio is 4 degrees, a conventional HVAC system would have to be designed to overcome a 68 degree difference.

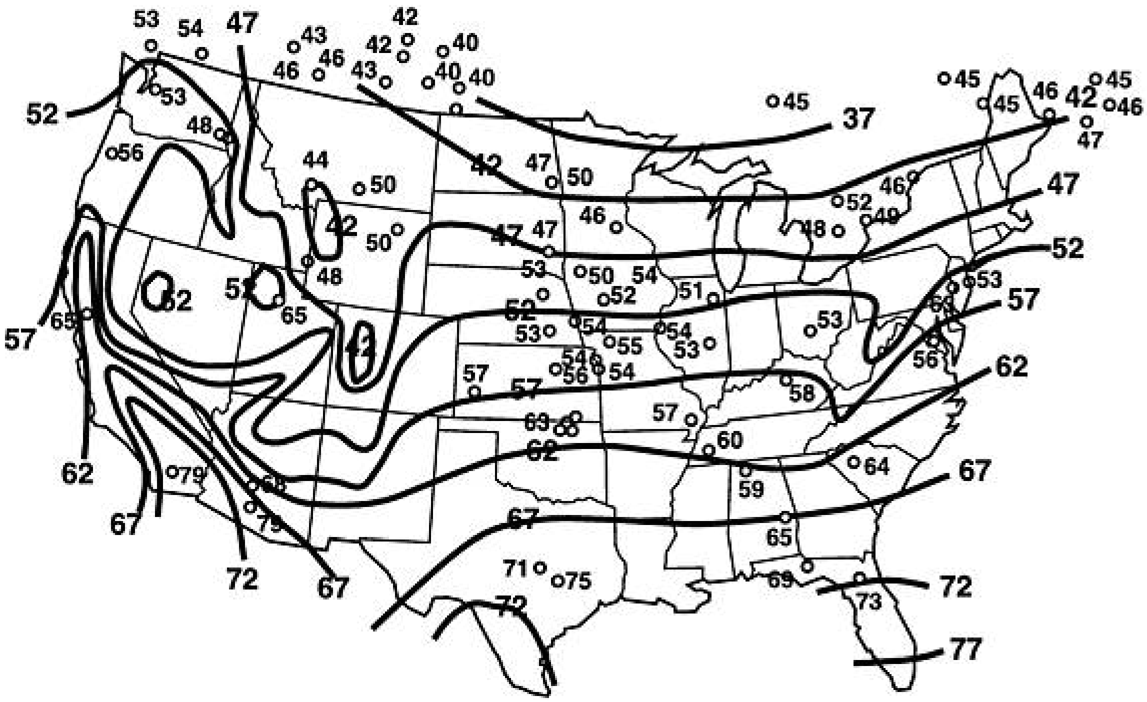


Figure 7. Mean Earth Temperature, Fahrenheit (DOE, 2003a)

GSHPs extract or reject the heat from the ground through a network of closed- or open-loop piping. The piping system (normally, high-density polyethylene pipe) acts as the heat exchanger between the ground and the GSHP system. Typically, water or a water-antifreeze solution is circulated through the ground loops and acts as the heat transfer medium. Inside the home or building, the water or water-antifreeze solution is sent through the condenser, where it transfers the heat from the ground to the building (for heating) or rejects the building's heat to the ground (for cooling). Figure 8 depicts the operation of a closed-loop GSHP system during the summer. Note that the vapor-compression cycle components (condenser, compressor, expansion valve, and evaporator) are located in the house, while the ground loop is buried in the soil. As a result, no outdoor equipment is utilized (Kavanaugh and Rafferty, 1997).

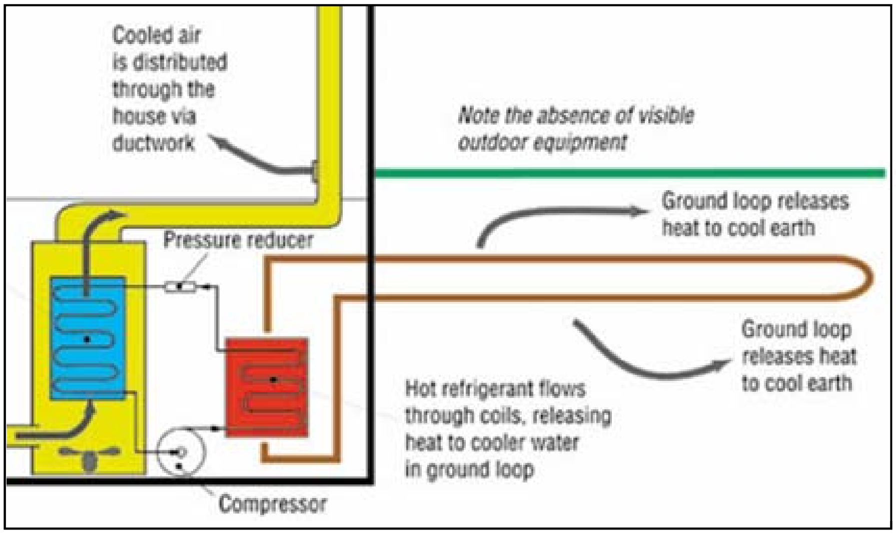


Figure 8. Closed-loop GSHP Operation during the Summer

Benefits of Ground Source Heat Pumps

GSHPs for facility heating, cooling, and domestic hot water heating have been proven to reduce HVAC energy consumption in commercial and military facilities. Consequently, GSHPs usually have lower life cycle costs than conventional HVAC systems. In a recent study of four elementary schools in Lincoln, Nebraska, the life cycle costs of GSHPs were found to be at least 15% lower than three other HVAC options. GSHPs also had the lowest total pollutant emissions of any of the technologies considered (Shonder, Martin, McLain, and Hughes, 2000). At Fort Polk Army Base, Louisiana, the HVAC systems of 4,003 military family housing units were converted to GSHPs. The use of GSHPs, along with other energy savings measures such as lighting retrofits, resulted in a 32% reduction in electrical consumption. Further, the base reported a savings of 26 billion British Thermal Units (BTUs) of natural gas per year (Hughes, Shonder, Gordon, and Giffin, 1997).

GSHPs have also been shown to have considerably reduced service and maintenance costs. In a study of 38 commercial and institutional buildings throughout the United States and Canada, the annual maintenance and service costs of GSHPs were found to be between 6.73 and 9.21 cents per square foot. Conversely, the annual maintenance and service costs of conventional HVAC systems are between 31.72 and 86.02 cents per square foot (Cane and Garnet, 2000).

The use of GSHPs is made even more attractive by the fact that it is considered a renewable energy source. Because of these advantages, the military has significantly increased its use of GSHPs. Indeed, in 1999, five companies were selected to manage over $500 million in military geothermal heat pump projects. At the time, Bill Richardson, Secretary of Energy, estimated that GSHPs would save the government as much as $700 million annually by the year 2005 (Denton, 1999).

Besides cost, GSHPs have a number of other benefits, including reduced space requirements, quieter operation, and increased reliability (DOE, 2003a). GSHPs also offer clear benefits for military applications. Unlike conventional HVAC systems, the equipment for GSHPs is located completely indoors and underground, which reduces the vulnerability of the system. In addition, the design of GSHPs is relatively simple when compared to conventional HVAC systems, since GSHPs primarily consist of piping and unitary heat pumps that operate efficiently even without precise water flow control (Kavanaugh, 1998). As conventional HVAC systems become more and more complex and less maintainable by the average mechanic, a return to simpler systems, such as GSHPs, may have clear advantages.

Types of Ground Source Heat Pumps

Ground source heat pumps are categorized by the type of ground-coupling system in use. There are three main types of ground-coupling systems: closed-loop, open-loop, and direction expansion. The type of ground-coupling system determines many factors, including performance characteristics, installation costs, and energy requirements. The following sections describe each of the GSHP types.

Closed-loop Systems

Closed-loop systems are the most common type of GSHP in the United States (Sachs and Dinse, 2000). A closed-loop system utilizes a sealed, underground network of high-strength piping for heat exchange between the earth and the refrigerant. Typically, water or a water-antifreeze solution is used as the heat transfer fluid. The system works by mechanically pumping the fluid through the underground loop until a desired temperature is reached. As the fluid travels through the loop, it absorbs heat from the earth for heating or rejects heat to the earth for cooling (DOE, 2003a). Figure 9 depicts several different configurations of closed-loop systems.

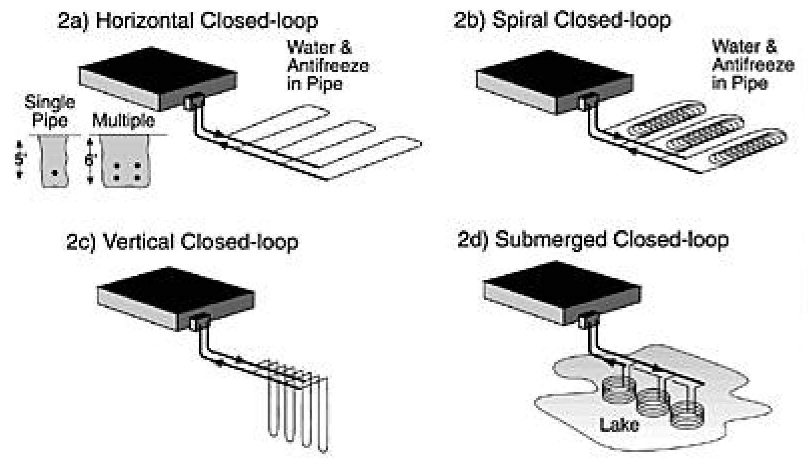


Figure 9. Closed-loop Ground-Coupling Systems (DOE, 2003a)

Each of the closed-loop systems has unique advantages and disadvantages. Horizontal closed-loop systems consist of piping placed in shallow trenches (at depths of 4 to 10 feet). Because only trenching is required, horizontal closed-loop systems typically have lower costs than systems that require well-drilling. However, horizontal closed-loop systems require a relatively large ground area for its piping. In addition, the piping is subject to increased ground temperature variance due to the shallow depth of the trenching. Because of the extensive ground area required, horizontal closed-loop systems are not common in commercial applications (DOE, 2003a).

Similar to horizontal systems, spiral closed-loop systems consist of piping placed in shallow trenches. However, spiral systems utilize circular loops, often referred to as the “slinky.” Because of the circular configuration of the piping, spiral systems require less trenching and ground area than horizontal systems. Consequently, spiral systems can have lower installation costs. However, spiral systems require more total piping. In addition, spiral systems have the same disadvantages (i.e. large ground area required and

increased ground temperature variation) as horizontal systems when compared to other closed-loop systems (DOE, 2003a).

Vertical closed-loop systems utilize wells that are bored at depths of 75 to 300 feet. They are advantageous in areas with limited land area, deep water table, and rocky or bedrock ground. Compared to other closed-loop systems, vertical systems require less total pipe length, less pumping energy, and less surface ground area. In addition, vertical systems are subject to less ground temperature variation due to the depth of the wells. However, vertical systems require drilling equipment to install, resulting in a high initial cost when compared to other closed-loop systems (DOE, 2003a).

Submerged closed-loop systems consist of piping submerged in a pond or lake. In some instances, a pond or lake can be artificially created as part of the installation of a submerged system. Compared to other closed-loop systems, submerged systems can require the least total pipe length. However, the obvious disadvantage of submerged systems is the requirement of a large body of water. Additionally, submerged systems often have special design considerations that require the expertise of an engineer experienced with submerged systems (DOE, 2003a).

Open-loop Systems

Instead of using a sealed fluid, open-loop systems make use of ground water as the heat transfer medium. They are often referred to as "ground-water-source heat pumps." Open-loop systems consist of extraction wells, extraction and reinjection wells, or surface water systems (see Figure 10). Each system works by obtaining ground water

from an extraction well or a surface water source, circulating the water through the heat exchanger, and returning the water to the source or reinjection well.

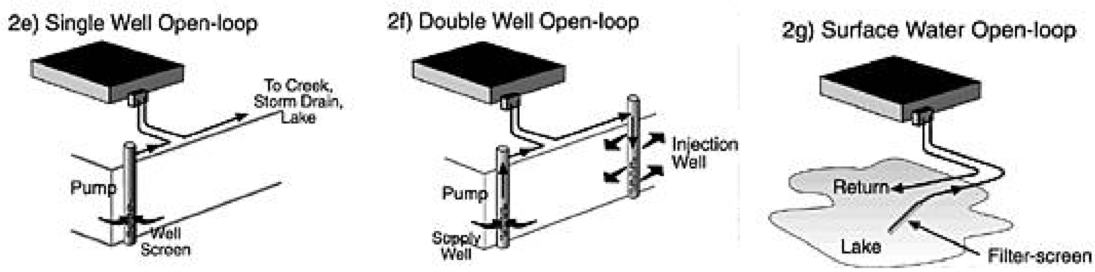


Figure 10. Open-loop Ground-Coupling Systems (DOE, 2003a)

Open-loop systems have a number of advantages when compared to closed-loop systems. Under ideal conditions, open-loop systems can be the most economical ground-coupling system because of the reduced drilling requirements and improved thermodynamic performance. In addition, the design of open-loop systems can be integrated with local water supply and irrigation functions. However, open-loop systems also have a number of disadvantages. Because of the dependency on local ground water, open-loop systems are limited by the availability of water. Even in instances where water is readily available, open-loop systems may require permits based on federal, state, and local water codes and regulations. The open-loop design is also vulnerable to any corrosive agents and biological contaminants in the water supply. Further, open-loop systems have the highest pumping power requirement of any GSHP system (DOE, 2003a).

Direct Expansion Systems

Unlike closed-loop and open-loop systems, direct expansion systems require no intermediate heat transfer fluid to transfer heat from the earth to the refrigerant. This eliminates the need for a fluid-refrigerant heat exchanger, a circulation pump, and the intermediate fluid. Instead of circulating water or a water-antifreeze solution, direct expansion systems circulate the chemical refrigerant through the ground, resulting in a direct heat exchange between the refrigerant and the earth. As a result, direct expansion systems have better heat transfer characteristics than other ground-coupling systems (DOE, 2003a). However, few states allow the use of direct expansion GSHPs because of the risk of leaking refrigerant (Den Braven, 1998). Figure 11 depicts a typical direct expansion configuration.

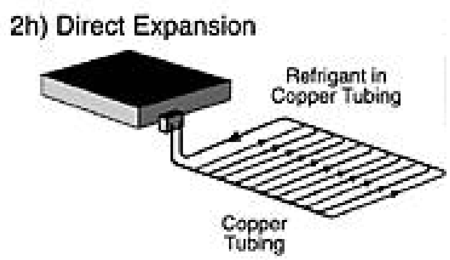


Figure 11. Direct Expansion Ground-Coupling System (DOE, 2003a)

HVAC Selection

When designing HVAC systems, design engineers have a number of competing objectives to consider. Table 2 provides some typical design considerations for HVAC selection. According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), these objectives are interrelated and the design

engineer must "consider how each factor affects the others. The relative impact of these [objectives] differs with different owners and often changes form one project to another for the same owner" (Howell et al., 1998).

Table 2. Common Design Considerations for HVAC Selection (Howell et al., 1998)

Load Dynamics	Reliability
Performance Requirements	Flexibility
Availability of Equipment	Operations Requirements
Capacity	Serviceability
Spatial Requirements	Maintainability
First Cost	Availability of Service
Energy Consumption	Availability of Replacement Components
Operating Cost	Environmental Requirements
Simplicity	

Despite these competing considerations, no design guidance or established criteria for HVAC selection has been developed for Air Force applications. Often, first cost is the only determining factor for HVAC selection. Consequently, it is difficult to promote an HVAC alternative that has clear advantages in other objectives, especially if it carries a higher first cost. In addition, HVAC designers usually specify alternatives that they are very familiar with or are readily available in the local area. This type of decision-making is known as alternative-focused thinking. Alternative-focused thinking has a number of shortcomings that will be discussed in the following sections. For a complex decision such as HVAC selection that involves multiple objectives, there is a clear need to utilize an objective approach that can account for the relative impact of competing objectives.

Decision Theory

According to Kirkwood (1997), the one essential element of a decision problem is the existence of at least two alternatives. When there is little difference in the outcomes of the alternatives, the decision problem is simple and requires little or no analysis. However, in most decisions, the alternatives have distinct consequences or outcomes. In addition, decisions usually involve tradeoffs between objectives (Kirkwood, 1997). The overall goal of any decision problem is to avoid undesirable consequences and attain desirable ones (Keeney, 1992).

There are two concepts that guide the decision process and provide a basis for evaluation: values and objectives. Values “are what we care about” (Keeney, 1992). They are the principles that are used to compare alternatives. When an alternative is said to be preferred, the implication is that the superior alternative achieves more of the desired values of the decision-maker than the inferior alternative(s). Objectives are developed to make a decision-maker’s values explicit. An objective is “a statement of something that one desires to achieve” (Keeney, 1992). Keeney (1992) categorizes objectives as either fundamental objectives or means objectives. Fundamental objectives represent the primary reasons for interest in a decision. Means objectives are objectives that are developed to achieve the fundamental objectives (Keeney, 1992).

For decision-makers, trying to evaluate differing alternatives against objectives presents a number of challenges. First, it is difficult to determine what things are important in evaluating the outcomes of decisions. As a result, decisions are often made without identifying the decision-maker’s true values and objectives. A second challenge for decision-makers is the difficulty in determining the relative importance of different

attributes of the decision. For example, when buying an automobile, how does cost compare in importance to performance? To obtain high performance, one typically pays a premium. Similarly, to keep cost low, concessions in performance are often made. Ranking alternatives based on the different tradeoffs between cost and performance can be difficult. The third challenge in decision-making is the difficulty in gauging the consequences that will result from each alternative. That is, there is uncertainty in every decision (Kirkwood, 1997).

The appropriate approach to solving decision problems varies, depending on the context of the problem. This research considered two different methodologies: alternative-focused thinking and value-focused thinking. The most common approach, known as alternative-focused thinking, uses available alternatives as the basis for the decision. The second approach, known as value-focused thinking, uses the decision-maker's values as the basis for the decision (Keeney, 1992). A comparison of alternative-focused thinking and value-focused thinking is presented in the next section.

Alternative-Focused Thinking Versus Value-Focused Thinking

The typical decision-making process begins when a decision problem is identified. Based on the identified problem, the next step is to quickly generate alternatives. Often, there is no scientific approach to selecting these alternatives. They tend to be obvious choices, either the most readily available options or alternatives that are very familiar to the decision-maker. Once the alternatives have been identified, the last step is to create some criteria for evaluating the chosen alternatives, so that the "best"

option can be selected. This type of decision-making is referred to as alternative-focused thinking (Keeney, 1992).

Alternative-focused thinking is a simple approach to decision problems. In many ways, it is the natural way of making a decision. The "tendency in all problem solving is to move away from the ill-defined to the well-defined" (Keeney, 1992). By narrowing the focus of a decision problem to a few obvious alternatives, decision-makers feel like they are making progress towards a solution (Keeney, 1992).

However, alternative-focused thinking has some major shortcomings. When only specific alternatives are considered, it is possible that much better alternatives are not identified. In effect, the exclusion of possible alternatives means that the decision-maker is not choosing the best option, but rather, the least-worst alternative (Weir, 2004). In addition, by focusing on alternatives, the criteria used for evaluation are often unrelated to the fundamental objectives. Often, one particular alternative, which is designated as the "favorite," is used as an anchor for evaluating other alternatives. In effect, the basis for the decision hinges on how well the alternatives compare to the favorite, instead of how well the alternatives meet the decision-maker's values (Keeney, 1992).

Like alternative-focused thinking, value-focused thinking begins when a decision problem is identified. However, the next step in value-focused thinking is not to generate alternatives, but to specify the decision-maker's values. Since values are what the decision-maker cares about, Keeney (1992) states that values are more fundamental to a decision than alternatives. Thus, values should be the basis for decisions. Once the values are defined, alternatives are sought that best meet the objectives of the decision-maker. The assertion is that because the VFT approach clarifies what is important to the

decision-maker first, the decision-maker is then able to select better alternatives for evaluation (Keeney, 1992). Table 3 provides a comparison of alternative-focused thinking and value-focused thinking for decision problems.

Table 3. Comparison of Alternative-Focused Thinking and Value-Focused Thinking (Keeney, 1992)

Alternative-focused thinking	Value-focused thinking
1. Recognize a decision problem	1. Recognize a decision problem
2. Identify alternatives	2. Specify values
3. Specify values	3. Create alternatives
4. Evaluate alternatives	4. Evaluate alternatives
5. Select an alternative	5. Select an alternative

Notice that the five activities in both approaches are the same. The only difference is the order of activities 2 and 3. This subtle structural variation explains the primary difference between the two approaches. Specifically, the two approaches differ in how they consider alternatives. With alternative-focused thinking, the alternatives are *identified*. Typically, the decision-making process begins only after two or more alternatives present themselves. Thus, alternative-focused thinking is a reactive approach to decision-making. In contrast, the VFT approach *creates* alternatives. When the fundamental objectives are explicitly known, the decision-maker can seek alternatives that provide the best possible consequences. Thus, value-focused thinking is a proactive approach to decision-making (Keeney, 1992).

Benefits of Value-Focused Thinking

There are a number of advantages of using value-focused thinking. First, it provides a highly structured approach to decision-making. Competing objectives are identified and ranked in terms of their relative importance to the decision-maker. This allows for strategic thinking and ensures that all key aspects of a decision are considered, thereby increasing the likelihood of selecting an optimal solution (Kirkwood, 1997). Second, VFT utilizes a mathematical approach that is objective, defendable, and repeatable. Because the values and their relative importance are determined before alternatives are considered, there is less risk of bias in the evaluation process. Consequently, decision-makers are able to clearly articulate why a particular alternative was selected and how well the alternative meets the organization's objectives (Weir, 2004).

Keeney (1992) states that there are a number of other advantages of using value-focused thinking. These include uncovering hidden objectives, guiding information collection, improving communication, facilitating involvement in multiple-stakeholder decisions, interconnecting decisions, evaluating alternatives, creating alternatives, identifying decision opportunities, and guiding strategic thinking (see Figure 12).

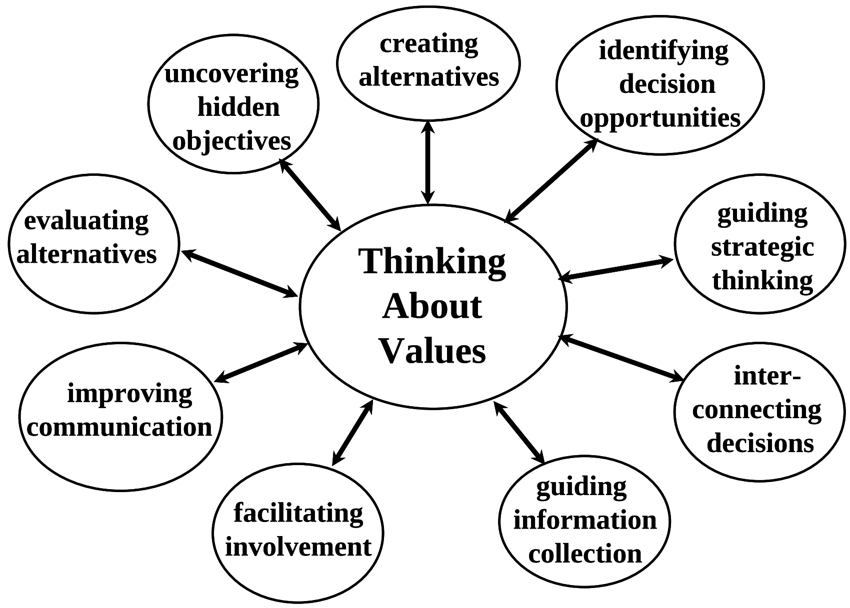


Figure 12. Benefits of Value-Focused Thinking (Keeney, 1992)

Ten-Step Value-Focused Thinking Process

This research utilizes a ten-step process to execute the principles of value-focused thinking. The ten-step methodology (see Figure 13) consists of identifying the problem, creating a value hierarchy, developing evaluation measures, creating single dimension value functions, weighting the value hierarchy, generating alternatives, scoring the alternatives, conducting deterministic analysis, conducting sensitivity analysis, and providing conclusions and recommendations (Shoviak, 2001). Although this process is not the only method of conducting a VFT analysis, it is the advantageous because it provides a good framework for capturing the decision-maker's values and evaluating alternatives (Weir, 2004). The first five steps deal directly with the creation of the value model and merit further discussion. Specifically, definitions of value hierarchies, evaluation measures, value functions, and evaluation weights are provided in the

following sections. The last five steps are more straightforward and will be covered in Chapters 4 and 5 of this research.

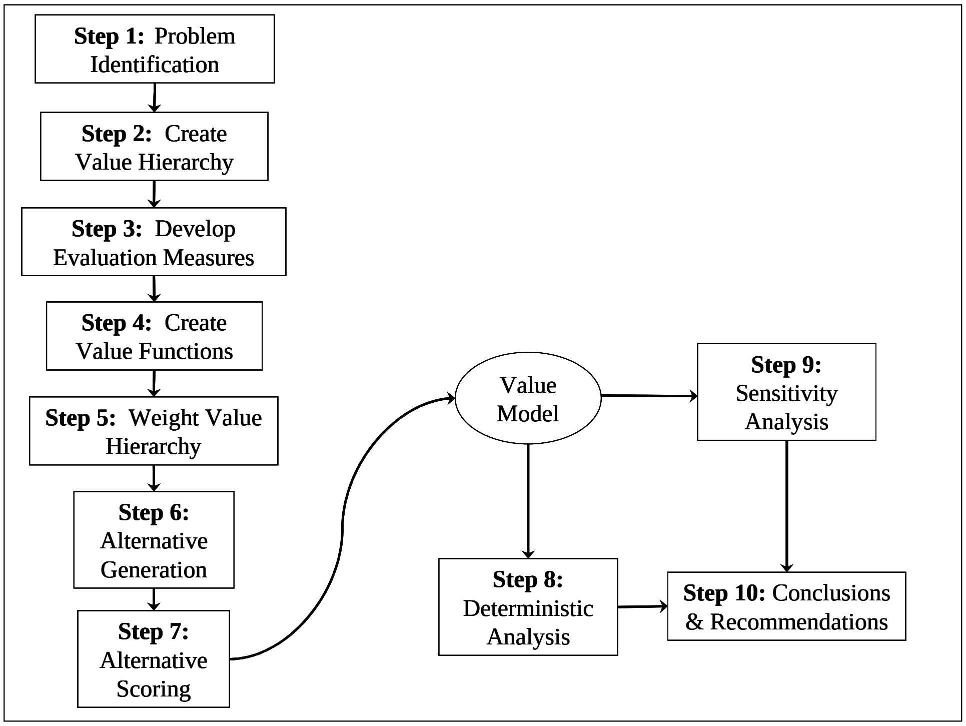


Figure 13. Value-Focused Thinking Ten-Step Process (Shoviak, 2001)

Value Hierarchy

After identifying a decision problem, the second step of the VFT process is to create a value hierarchy. A value hierarchy is a visual representation of the values and objectives of a specific decision analysis problem (Keeney, 1992). The actual hierarchy is a tree-like structure that consists of several tiers and branches. By definition, the evaluation considerations at the same distance from the top of the hierarchy constitute a single tier (Kirkwood, 1997). Branches, on the other hand, consist of all the measures and objectives under a fundamental objective (Weir, 2004). Figure 14 provides an

example of a generic value hierarchy with three tiers and two branches. Value hierarchies, however, are not limited in terms of the number of tiers or branches. A hierarchy should consist of enough tiers and branches to capture all of the relevant values and objectives of the decision-maker.

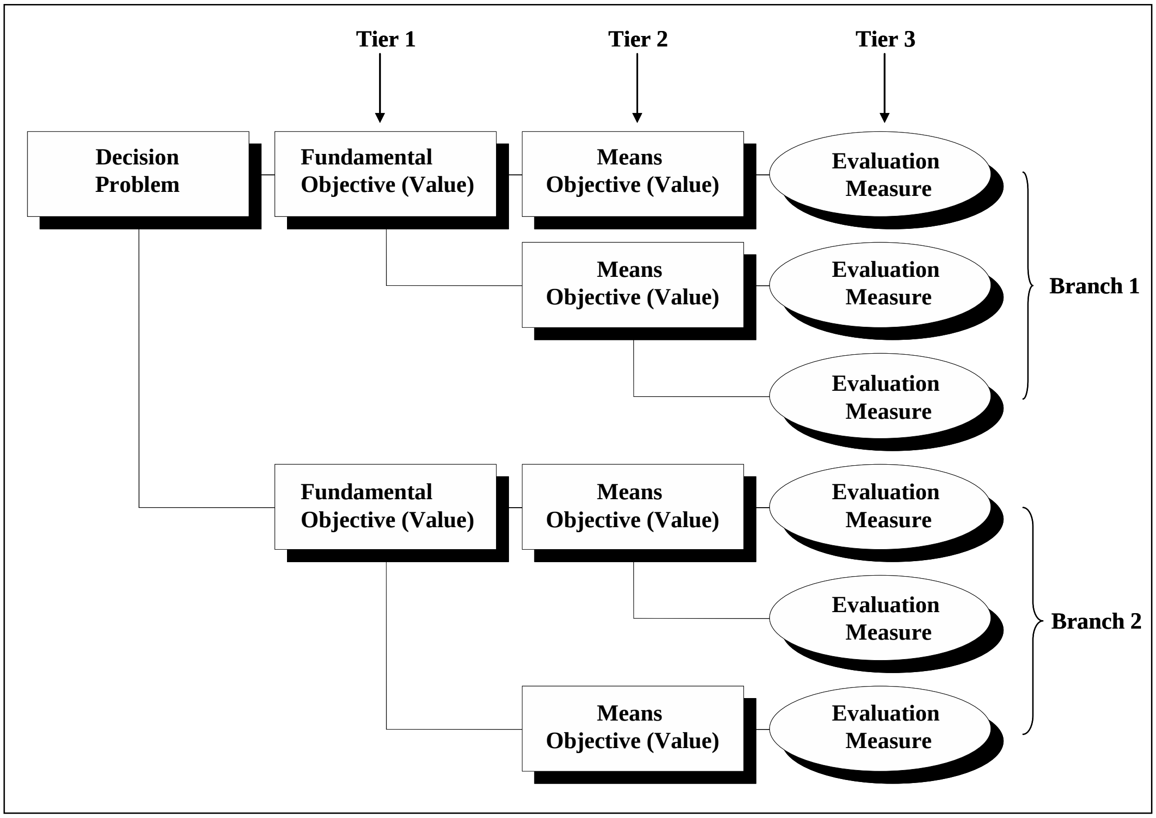


Figure 14. Generic Value Hierarchy

As illustrated in Figure 14, the overall decision problem is placed at the top of the hierarchy. For this research, the decision problem is "what is the best HVAC system (for a particular military installation)?" The decision problem is then subdivided into fundamental objectives, forming the first tier of the hierarchy. The fundamental

objectives are then subdivided into means objectives. This process of subdividing objectives continues until the evaluation measures are developed. Evaluation measures, which are the measuring scales for the degree of attainment of objectives, form the final tier of a value hierarchy (Kirkwood, 1997).

The development of a value hierarchy is important because it results in a “more accurate understanding of what one should care about in the decision context” (Keeney, 1992). By creating the hierarchy, the decision-maker can literally see what is important to the decision. In addition, the visual format of the hierarchy is useful because it helps identify any missing objectives. This increases the likelihood of capturing all the relevant values and objectives for a decision.

When developing a value hierarchy, there are five desirable properties that guide the process: completeness, nonredundancy, independence, operability, and small size. To be complete, a hierarchy should be collectively exhaustive such that all concerns relevant to a decision problem are included. To be nonredundant, the evaluation considerations should be mutually exclusive. That is, the evaluation considerations should not overlap within a single tier of the hierarchy (Kirkwood, 1997). To be independent, the preference for the level of one evaluation measure should not depend on the level of another evaluation measure (Weir, 2004). To be operable, a value hierarchy should be easily understandable to the individuals who will use it. Finally, all things being equal, a small value hierarchy is desirable (Kirkwood, 1997). Besides being less intimidating, a small hierarchy is easier to communicate and requires fewer resources to evaluate alternatives (Weir, 2004).

Evaluation Measures

After the value hierarchy is created, the next step is to develop evaluation measures. As mentioned previously, an evaluation measure is a measuring scale for the degree of attainment of an objective. According to Kirkwood (1997), evaluation measures can be classified as either natural or constructed. A natural scale is one that is in general use and is commonly interpreted by all. For example, life expectancy is commonly understood as the number of years that a person is expected to live. Conversely, a constructed scale is one that is developed for a particular objective. An example of a constructed scale is the security classification system used by the government, which regulates the control of classified information through constructed scales such as top-secret or secret (Kirkwood, 1997).

In addition to natural or constructed, evaluation measures are also classified as either direct or proxy. A direct scale measures the degree of attainment of an objective. Kirkwood (1997) uses profit in dollars as an example of a direct scale. A proxy scale focuses on the attainment of an associated objective. For instance, the gross national product can be a proxy scale for the economic standing of a nation (Kirkwood, 1997).

Table 4 provides examples of various evaluation measure scales.

Table 4. Examples of Evaluation Measures (Weir, 2004)

	Natural	Constructed
Direct	**Net Present Value** **Time to Remediate** **Cost to Remediate**	**Olympic Diving Scoring** **Weather Prediction Categories** **Project Funding Categories**
Proxy	**Gross National Product** **(Economic growth)** **Site Cleanup** **(Time to Remediate)**	**Performance Evaluation Categories** **(Promotion Potential)** **Instructor Evaluation Scales** **(Instructor Quality)**

Single Dimension Value Functions

In order to rank alternatives, the evaluation measures must be combined into a single index that measures overall desirability. This can be difficult because each measure has different units and ranges of variation. In addition, the model must account for measures that have increasing or decreasing returns to scale. To address these difficulties, a single dimension value function (SDVF) is assigned to each evaluation measure (Kirkwood, 1997). As depicted in Figure 15, a SDVF is a mathematical function (in the form of a piecewise or exponential graph) that can take the form of a linear, concave, convex, or s-shaped line depending on the appropriate returns to scale (Weir, 2004). The score of an evaluation measure is represented on the *x*-axis of a SDVF, while the value of the evaluation measure is represented on the *y*-axis.

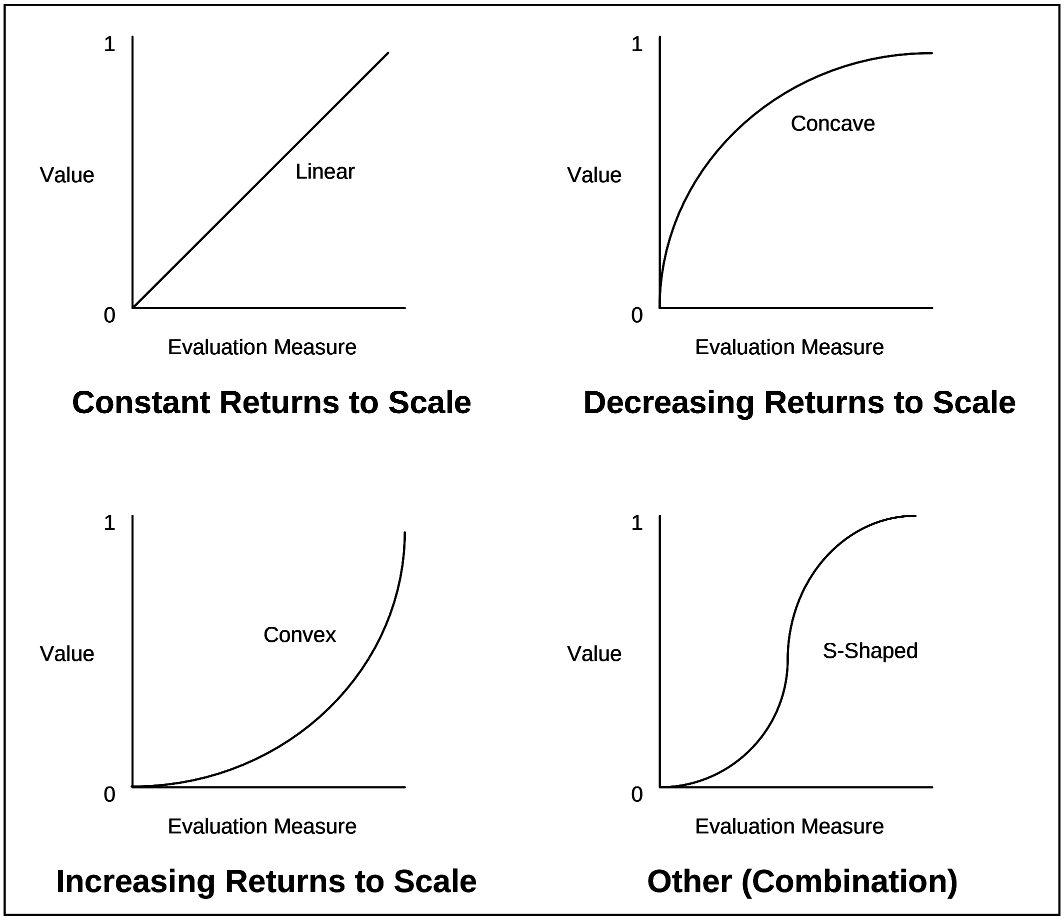


Figure 15. Generic Single Dimension Value Functions (Weir, 2004)

Regardless of the shape, SDVFs have some common properties. All SDVFs convert the score of an evaluation measure into a unitless value, normally between 0 and 1. By convention, the least desirable measurement is given a value of 0, while the most desirable is given a value of 1. In addition, SDVFs display monotonic behavior. That is, higher levels of an evaluation measure are always either more preferred or less preferred, regardless of the levels of the other measures (Kirkwood, 1997).

Evaluation Weights

The final step in the development of the value model is the weighting of the value hierarchy. This accounts for the differing levels of importance of each evaluation measure. There are two common approaches for weighting a value model: global and local. With global weighting, the weights are first assigned to the evaluation measures across the bottom tier of the hierarchy. Typically, the weights are assigned so that the sum of the weights across the bottom tier equals 1. The weights of each preceding objective are then calculated by summing the weights of the measures directly below the objective. Figure 16 provides a generic example of global weighting. Because global weighting starts with the bottom tier and moves up, global weighting is known as a bottom-up approach to weighting (Weir, 2004).

The advantage of global weighting is that each evaluation measure is directly compared with every other evaluation measure. As a result, the weights are more likely to reflect the decision-maker's true preferences. However, global weighting becomes increasingly complex as the number of measures increases. For example, consider a value model with 100 evaluation measures. Determining the importance of one measure in relation to the other 99 measures is likely to be difficult and time-consuming. Thus, global weighting is more advantageous with smaller value hierarchies.

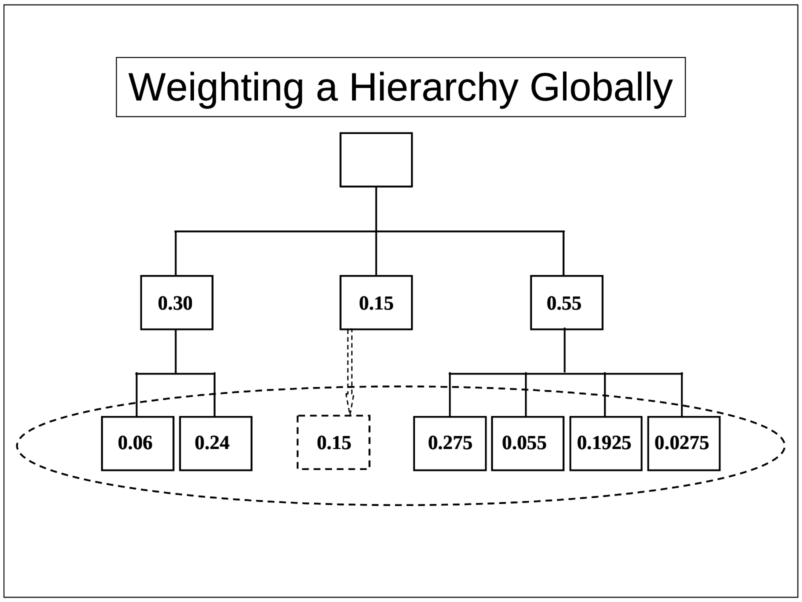


Figure 16. Example of Global Weighting (Weir, 2004)

With local weighting, the weights are first assigned to the top tier of values. Then, weights are assigned to individual tiers within each branch of the model. The weights of a tier within a branch are assigned such that the sum equals 1. Once all the local weights are determined, the global weights for each evaluation measure can be determined by multiplying the local weight of a measure with the local weights of each objective directly above the measure. Figure 17 provides a generic example of local weighting (with the global weights shown in parentheses below the bottom tier). Because local weighting starts with the top tier and moves down, local weighting is known as a top-down approach to weighting (Weir, 2004).

Unlike global weighting, local weighting is conducted in a piecemeal fashion. That is, each tier within a branch is weighted separated from other tiers within other branches. As a result, fewer values or measures are considered at any one time. Thus,

the main advantage of local weighting is the reduced complexity of assigning weights. However, when measures and values are weighted separately, there is a greater likelihood that the global weights will not reflect the true preferences of the decision-maker. Consequently, local weighting often requires continuous feedback between the model builder and the decision-maker in order to ensure that the global weights are indicative of the decision-maker's preferences.

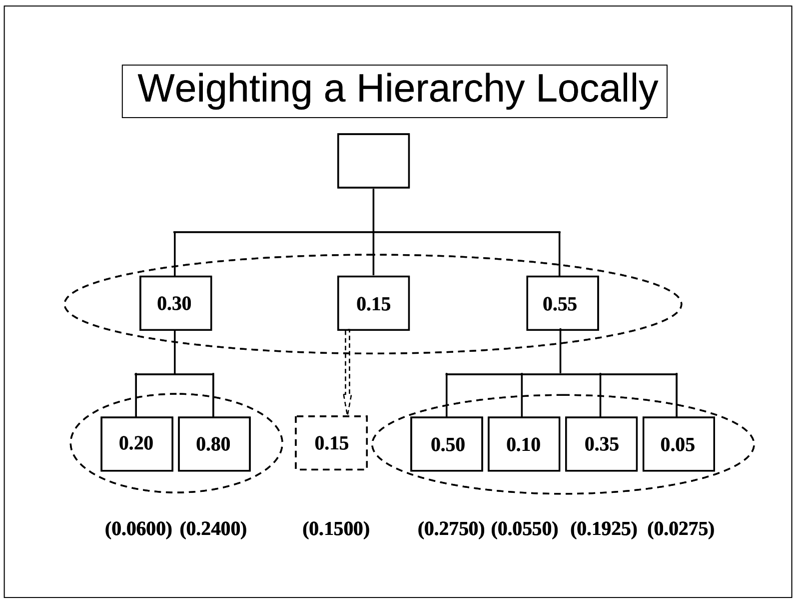


Figure 17. Example of Local Weighting (Weir, 2004)

III. Methodology

Overview

Because the selection of a heating, ventilating, and air-conditioning (HVAC) system involves multiple objectives, value-focused thinking (VFT) was selected as the most appropriate decision analysis methodology. This chapter outlines the first six steps of the ten-step VFT process as described in Chapter 2. Using the VFT process, this research determined the values that are important when selecting HVAC systems. Next, appropriate evaluation measures for each value were constructed, and the weights of each value and measure were formulated. The final value model provides military decision-makers (such as a base commanders, Base Civil Engineers (BCEs), or base energy managers) immediate feedback on the practicality of installing ground-source heat pumps (GSHPs) for a specific building at a particular installation.

Step One: Problem Identification

The Air Force Civil Engineer Support Agency (AFCESA) recognized the potential of ground source heat pumps to reduce HVAC energy consumption in government facilities. Unfortunately, the GSHP is often viewed as a cost prohibitive, new technology despite life-cycle cost calculations that suggest otherwise. In addition, HVAC designers lack established criteria for comparing GSHPs and conventional HVAC systems. The implication is that designers and decision-makers are not even considering GSHPs as an option. Thus, AFCESA asked AFIT to develop a fact-based rationale for

the use of GSHPs in lieu of conventional HVAC systems. This VFT model will serve as the basis for comparison of GSHPs and conventional options.

Step Two: Create Value Hierarchy

There are two main ways to develop a value hierarchy: top-down and bottom-up. Typically, a top-down or objectives-driven approach is used when the alternatives are not well defined at the start of the analysis. This approach starts with the overall objective and subdivides it until the evaluation considerations are developed. When the alternatives are well-known, a bottom-up or alternatives-driven approach may be appropriate. In this approach, the alternatives are analyzed to determine how they differ, and evaluation measures are created based on these differences. Then, the measures are grouped together to form the higher layers of the hierarchy (Kirkwood, 1997).

For this research, a bottom-up approach could have been used because the alternatives of interest are already known. Indeed, a goal of this research was to provide a tool to compare GSHPs with conventional options. However, a value hierarchy developed using a bottom-up approach would only be valid for GSHPs. In locations where GSHPs are not viable, decision-makers should still consider other cost-effective, environmentally-friendly options if they are available. The overall intent of this research was to provide a tool for selecting the best HVAC option at an installation. For this reason, a top-down approach was utilized. Using this approach, the final model is not constrained to GSHPs and can be used for any available HVAC alternative.

The overall objective of this hierarchy was to select the best HVAC option for a particular location. The first step in creating the hierarchy was to subdivide the overall

objective into fundamental objectives. Based on a review of relevant literature and the researcher's experience, two questions are always asked when designing an HVAC system: (1) how much will it cost and (2) will it meet the performance requirements? These two questions form the first two fundamental objectives of the hierarchy – *Resources* and *Operation*. In recent times, a new question has surfaced and must be considered: will the system have an adverse impact on its surroundings? This question leads to the third fundamental objective – *Environmental Impact*. These objectives represent the first tier of values (see Figure 18), and are discussed separately below.

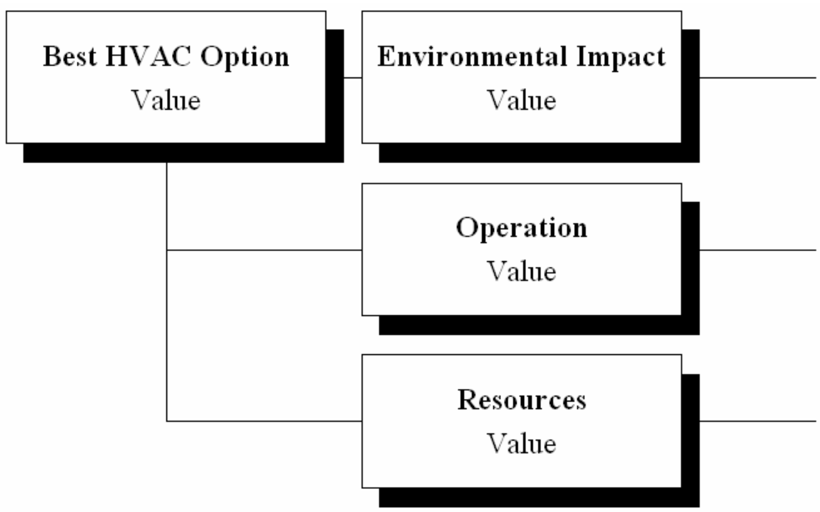


Figure 18. First Tier of the Value Hierarchy

Resources

The fundamental objective *Resources* refers to an organization's desire to utilize its resources in the most effective manner. Because nearly all organizations have limited resources, decision-makers are faced with difficult decisions regarding the proper

allocation of these resources. Consequently, HVAC systems must not only be designed to meet performance specifications, they must be designed to be economical as well. The selection often involves a tradeoff between the system's performance and its economic merits (Howell et al., 1998). *Cost* is introduced into the hierarchy as a means objective for the fundamental objective *Resources*. For this model, *Cost* refers to the owning, operating, and replacement costs of an HVAC system. The owning costs include the initial installation costs (both labor and materials). The operating costs include the costs for energy and fuel, operating and maintenance services, and materials and supplies. Finally, the replacement costs are the costs to replace equipment based on the projected service life of the system components. All things being equal, the objective is to minimize *Cost.* The *Resources* fundamental objective is shown in Figure 19.

It is important to note that the payback period was not considered for this model. The payback period is the length of time required for the cumulative cost savings of an energy-efficient HVAC system to equal the higher-initial installation cost of the equipment. The Department of Defense requires that energy projects have a 10-year or less payback (A-GRAM 99-22, 1999). There are two reasons why payback period was not considered. First, not every HVAC installation can be classified as an energy project. Certainly, payback period is a non-factor with designing conventional HVAC systems. As a result, including payback period would bias the model towards energy projects. Second, from an economic standpoint, payback period is limited because it fails to recognize the total benefit of an investment. That is, payback period only accounts for the time from initiation to payback and does not account for additional benefits for the rest of the equipment life. In addition, payback period disregards the time value of

money, essentially equating the value of a dollar today to the value of a dollar at the end of the payback period (Bloucher, Chen, Cokins, and Lin, 2005).

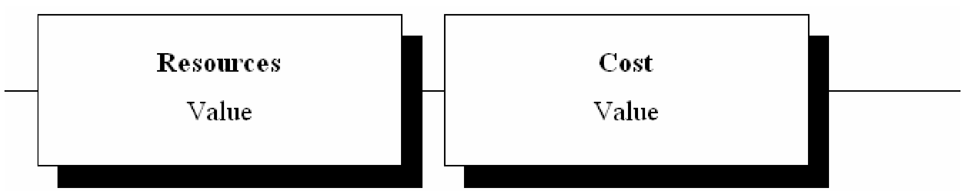


Figure 19. Resources Values

Operation

The fundamental objective *Operation* refers to an organization’s desire to select systems that provide maximum performance and require minimal maintenance. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the “primary function of a heating, ventilating, and air-conditioning (HVAC) system is either (1) the generation and maintenance of comfort for occupants in a conditioned space; or (2) the supplying of a set of environmental conditions (high temperature and high humidity; low temperature and high humidity, etc.) for a process or product within a space” (Howell et al., 1998). For most Air Force applications, the primary function of interest is the comfort of occupants. Thus, *Occupant Comfort* is included as the first means objective for *Operation* and is defined as the ability to provide a comfortable working environment for a building’s occupants. For buildings that require specific environmental standards, this means objective can simply be renamed to better reflect the objectives of the project.

The concept of human comfort is rather complex, involving knowledge of physiology, metabolic rate, clothing insulation, and moisture (Howell et al., 1998). For this research, ASHRAE Standard 55 was used as the basis for determining comfort. According to the standard, an environment is comfortable if 80% of the sedentary or slightly active persons find the environment thermally acceptable. ASHRAE identifies comfort "zones" that meet the 80% requirement. Figure 20 gives the comfort zones for both winter and summer based on typical summer and winter clothing. Generally, humans are comfortable if the relative humidity stays between 30% and 60%, and the temperature is between 70 and 80 degrees Fahrenheit.

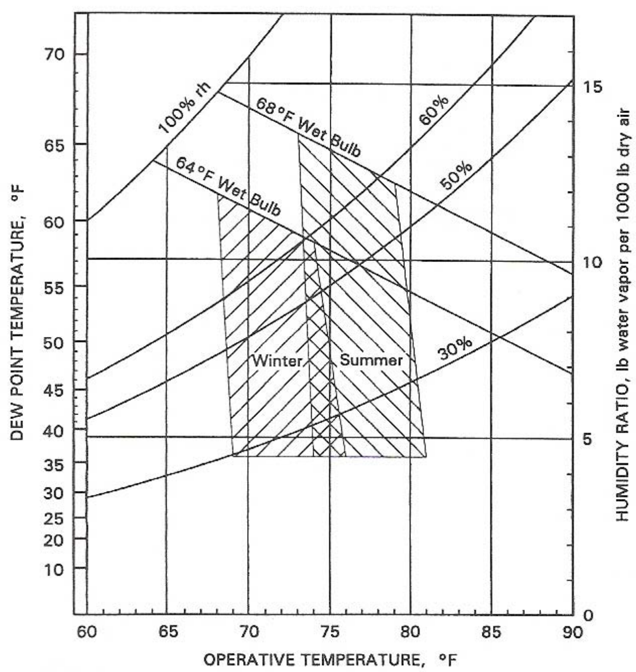


Figure 20. ASHRAE Summer and Winter Comfort Zones (Howell et al., 1998)

Maintaining a temperature and relative humidity in the comfort zones has additional benefits as well. Specifically, controlled humidity levels help dissipate electrostatic charges and prevent disease. Although it is not practical to eliminate all shocks (to do so would require that the relative humidity be kept above 65%), keeping the relative humidity above 35% is sufficient to eliminate most electrostatic shocks as shown in Figure 21. At 35% or higher, the amount of shocks is infrequent and should not trouble most people and office equipment (Harriman, Brundrett, and Kittler, 2001).

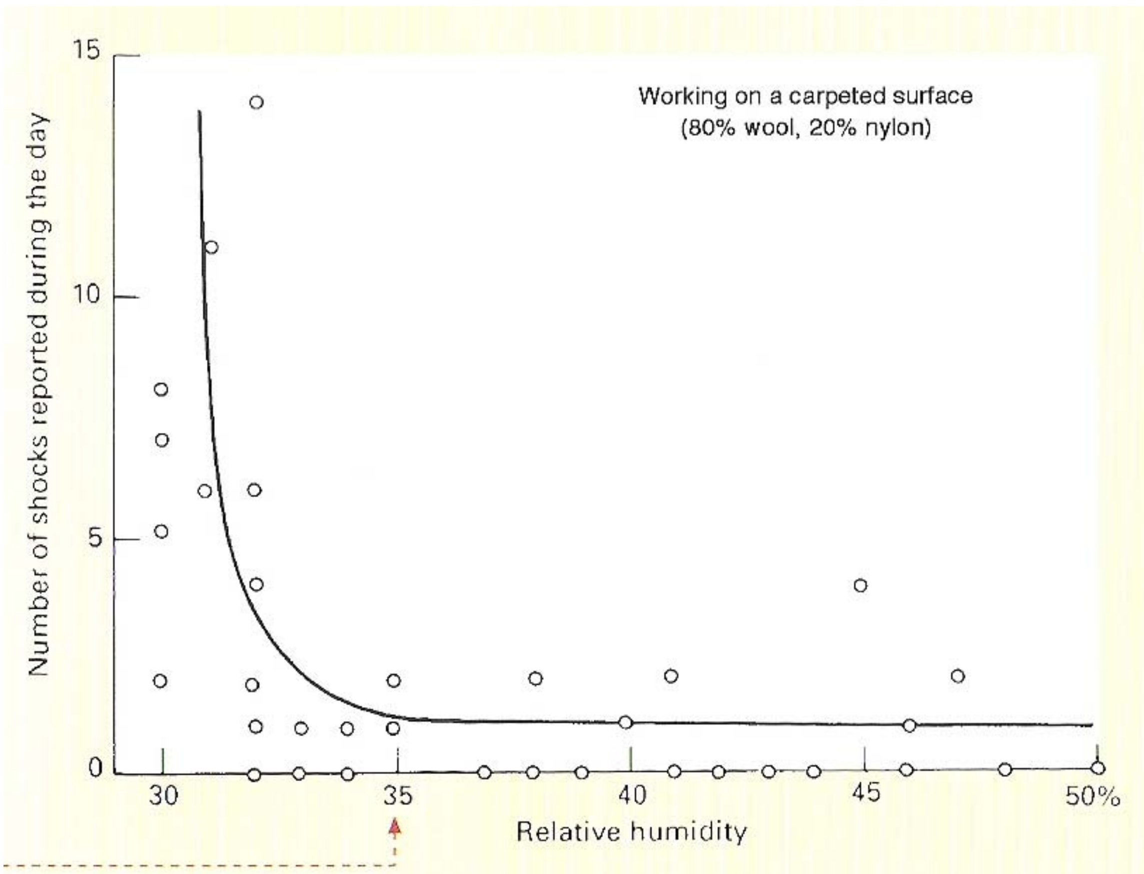


Figure 21. Frequency of Electrostatic Shocks based on Relative Humidity (Harriman et al., 2001)

In terms of disease, the mortality rate of certain organisms is the highest when the relative humidity is around 50%, although different organisms exhibit different characteristics (Howell et al., 1998). For office buildings, adverse health effects are not likely unless humidity is extreme for extended periods (Harriman et al, 2001). Thus, an HVAC system that can keep the humidity within the comfort levels is sufficient for typical commercial applications.

Maintainability is the second means objective and is defined as the difficulty in keeping the equipment in good operating condition. For this research, *Maintainability* does not factor in the cost of labor and materials for maintenance. Those costs are already included in the *Cost* means objective under *Resources*. Instead, *Maintainability* refers to the ease of conducting maintenance. For instance, consider two hypothetical HVAC systems, System A and System B, that require replacement parts. The cost for replacement parts for both systems are the same, but System A's parts are readily available in the local area, while System B's parts must be ordered and arrive 3 days later. In the end, the direct cost of maintenance is the same for both systems, but System A would be advantageous because it is relatively easier to maintain than System B. Overall, the fundamental objective of *Operation* is shown in Figure 22.

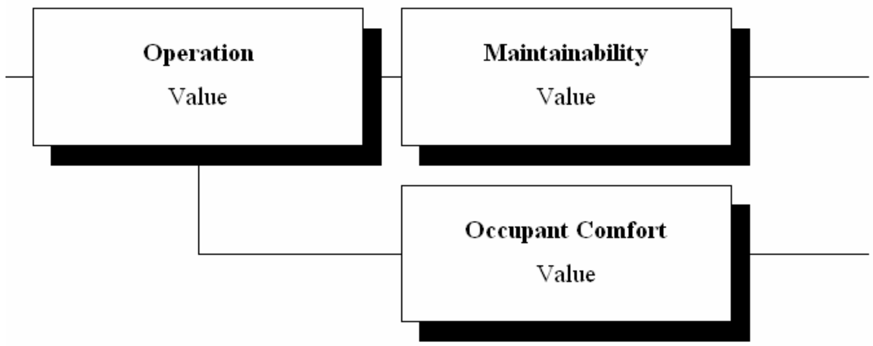


Figure 22. Operation Values

Environmental Impact

The fundamental objective *Environmental Impact* refers to an organization's desire to minimize the impact of the HVAC system on its surroundings. This includes both the pollution caused by the consumption of energy and the physical impact of the HVAC components on its surroundings. The first means objective *Aesthetics* accounts for the physical impact of the HVAC system and is defined as the visual and acoustical impact of the HVAC system. Admittedly, this is a very subjective value, as different people will perceive HVAC components differently. What is an "eyesore" to one person may be hardly noticed by another. To accurately gauge this value, the decision-maker or designer must be acutely aware of the building occupants' preferences.

The second means objective to *Environmental Impact* is *Environmental Stewardship*. As the name of the value implies, *Environmental Stewardship* refers to the environmental friendliness of the HVAC system and is defined by the energy consumption of the system and its use of renewable technologies. In this case, it is important to again clarify that cost is not considered for this objective. It is not inconceivable for an HVAC system to reduce energy consumption but not annual

operating costs. A GSHP, for instance, relies almost solely on electrical power. In a cold weather environment where natural gas rates are low and electrical rates are high, switching from a conventional HVAC system (which uses natural gas for heating) to a GSHP system may have little to no impact on the monthly energy bill. However, lowering the energy consumption is advantageous because it helps an installation fulfill the energy reduction goals mandated by Executive Order 13123. In addition, reducing energy consumption or utilizing renewable energy can improve the public image or standing of an installation in its community. Overall, the fundamental objective of *Environmental Impact* is shown in Figure 23.

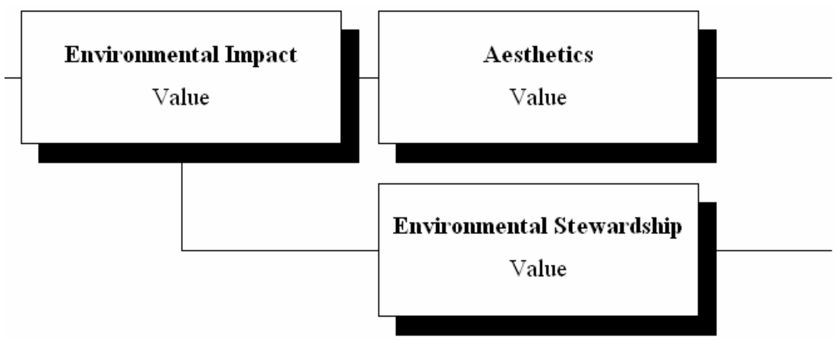


Figure 23. Environmental Impact Values

Step Three: Develop Evaluation Measures

The fundamental and means objectives developed in Step Two provide a qualitative value hierarchy that is useful in its own right. It can be used to guide information collection, identify alternatives, and to facilitate communication (Kirkwood, 1997). However, evaluation measures must be developed in order to conduct a quantitative evaluation of alternatives.

For this research, a total of 12 evaluation measures were developed. A complete listing of the evaluation measures are summarized in Table 5. Detailed definitions for each measure are included in Appendix A.

Table 5. Evaluation Measures for the Value Model

Means Objective	Measure	Scale Type	Measure Unit	Upper Bound	Lower Bound
Cost					
	Initial Cost	Natural Direct	Dollars	Facility Dependent	Facility Dependent
	O&M Cost	Natural Direct	Dollars	Facility Dependent	Facility Dependent
	Replacement Cost	Natural Direct	Dollars	Facility Dependent	Facility Dependent
Environmental Stewardship					
	Energy Consumption	Natural Direct	kwh	Facility Dependent	Facility Dependent
	Use of Renewable Technology	Constructed Proxy	Categorical	Renewable Technologies	No Renewable Technologies
Aesthetics					
	Visual Impact	Constructed Proxy	Categorical	Unobtrusive	Obtrusive
	Noise	Constructed Proxy	Categorical	Imperceptible	Noticeable
Occupant Comfort					
	Supply Air Temp (heating)	Natural Direct	Degrees (F)	95	70
	Dehumidification	Constructed Proxy	Categorical	Meets Requirements 100% of the time	Meets Requirements <98% of the time
Maintainability					
	Location of Equipment	Constructed Proxy	Categorical	Indoors/Easily Accessible	Outdoors/Difficult to Access
	Available Materials	Constructed Direct	Categorical	Within 50 Miles	50 Miles or More
	Available Service	Constructed Direct	Categorical	Within 50 Miles	50 Miles or More

The evaluation measures Initial Cost, O&M Cost, Replacement Cost and Energy Consumption merit further discussion. According to Table 5, the upper and lower bounds for these measures are classified as facility dependent. This accounts for the varying requirements of different facilities. For example, a small residential home would be expected to require a smaller HVAC system than a large office building. Consequently, the cost and energy consumption levels will vary depending on the size and function of a building. However, it may be more accurate to state that these measures are “cooling- and heating-load dependent.” An office building in temperate

San Diego, California will have vastly different requirements than a similar office building in Minneapolis, Minnesota.

For each individual HVAC project, it is left to the engineer or decision-maker to develop appropriate bounds for these measures. The goal is to pick bounds that allow for differentiation of alternatives. The overall value hierarchy is presented in Figure 24.

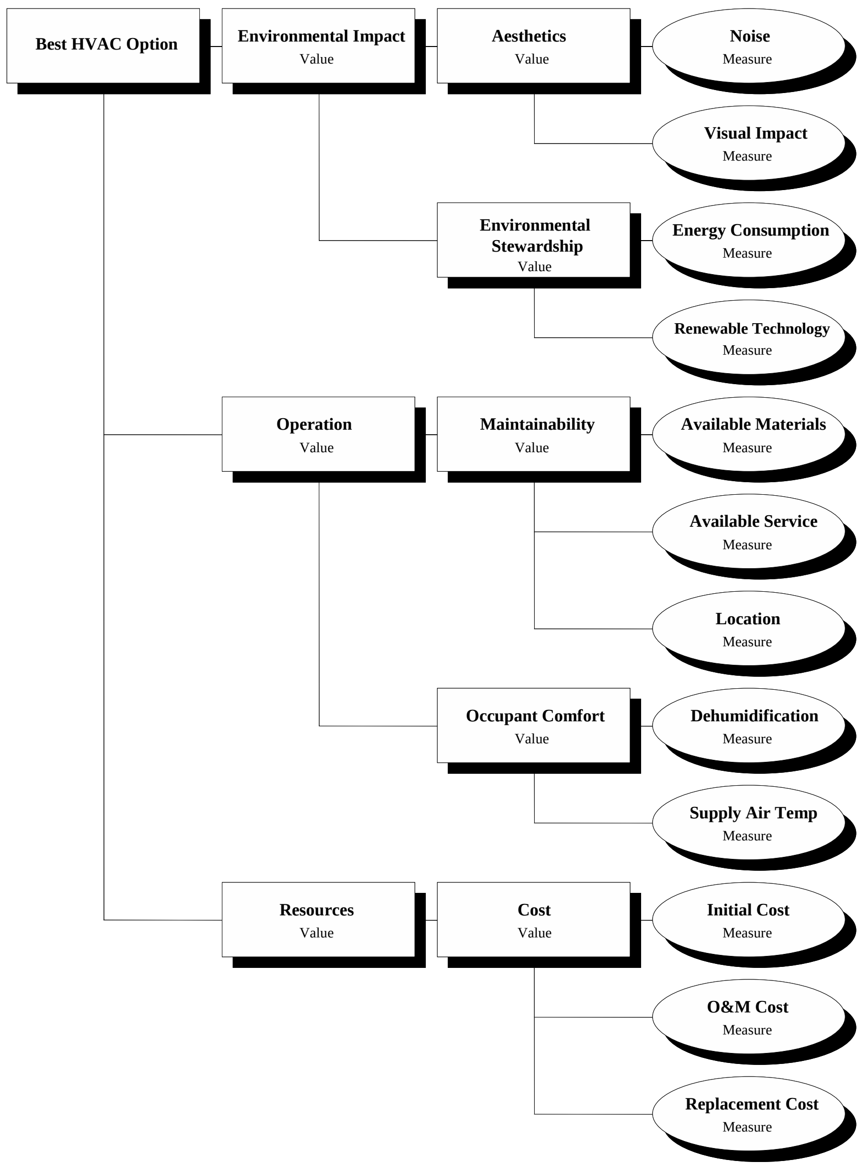


Figure 24. Overall Value Hierarchy

Step Four: Create Single Dimension Value Functions

Recall from Chapter 2 that the single dimension value function (SDVF) converts the score of each measure into a unitless value between 0 (least preferred) and 1 (most preferred). When an evaluation measure has a small number of possible scoring levels, a discrete SDVF is recommended by Kirkwood (Kirkwood, 1997). Otherwise, a continuous SDVF is appropriate. Figure 25 gives an example of both a discrete and continuous SDVF.

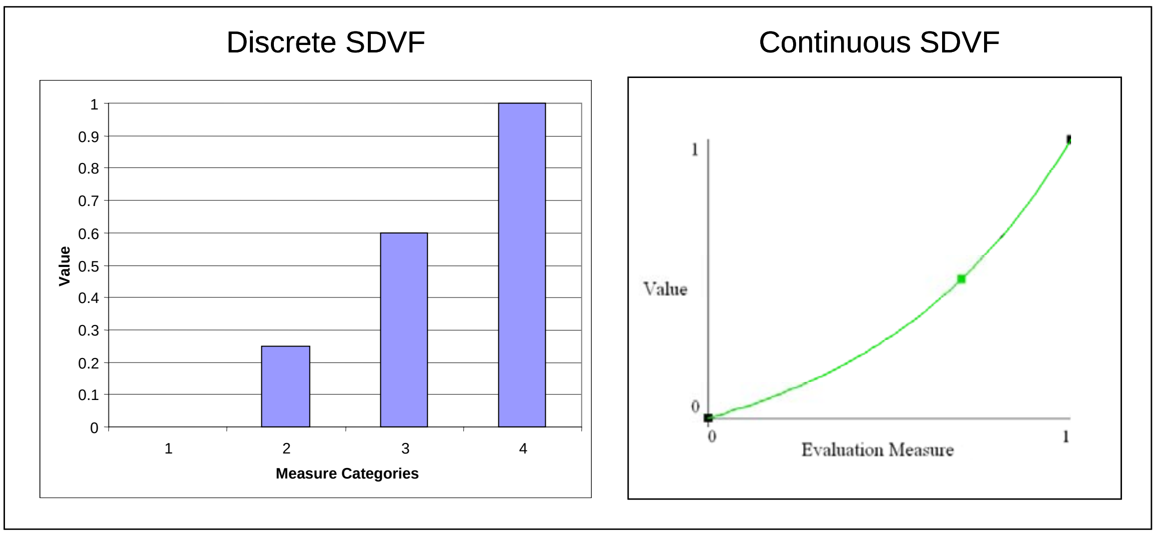


Figure 25. Generic Discrete and Continuous SDVFs

Continuous SDVFs can be represented with either piecewise linear functions or exponential functions. For this research, only exponential functions were utilized. Exponential value functions have a specific form as shown in Equations 1 and 2. Equation 1 is used when preferences are monotonically increasing over x. That is, higher

amounts of the evaluation measure are preferred. Conversely, Equation 2 is used when preferences are monotonically decreasing over *x*. As the equations indicate, exponential SDVFs depend on the range of the measure and a constant, known as the exponential constant. The exponential constant determines the specific shape of the function, and its shape is commonly determined by direct assessment from the decision-maker (Kirkwood, 1997).

$$\mathbf{v(x)} = \begin{cases} \dfrac{1-\exp\left[-(x-Low)/\rho\right]}{1-\exp\left[-(High-Low)/\rho\right]}, \rho \neq Infinity \\ \dfrac{x-Low}{High-Low}, otherwise \end{cases} \tag{1}$$

$$\mathbf{v(x)} = \begin{cases} \dfrac{1-\exp\left[-(High-x)/\rho\right]}{1-\exp\left[-(High-Low)/\rho\right]}, \rho \neq Infinity \\ \dfrac{High-x}{High-Low}, otherwise \end{cases} \tag{2}$$

where

v(x) = the exponential single dimensional value function

High = the upper bound of the measure

Low = the lower bound of the measure

ρ = exponential constant

For this research, seven measures (Use of Renewable Technology, Noise, Visual Impact, Dehumidification, Location of Equipment, Available Materials, and Available Service) were assigned discrete SDVFs. One measure (Supply Air Temperature) was represented by a monotonically increasing exponential function. Finally, four measures (Initial Cost, O&M Cost, Replacement Cost, and Energy Consumption) were assigned monotonically decreasing exponential functions. The single SDVF for each evaluation measure is provided in Appendix A.

The value model created in Steps One thru Four represents the generic design tool that can be used at any installation. It captures the Air Force's values and objectives regarding its HVAC systems. The slope of some of the SDVFs may need adjustment to reflect a particular decision-maker's preferences, but the behavior of the SDVFs should not change. For example, it is reasonable to assume that the behavior of the Initial Cost SDVF will remain monotonically decreasing.

The remaining steps of this research require customization for specific locations and facilities. The weights of the hierarchy, for instance, may be drastically different for a medical facility (where operation may be more important than cost) than for a storage facility. For this research, AFCESA asked that GSHPs be evaluated at three different locations around the country: a northern tier location (high heating demand), a central location, and a humid southern location (high cooling and dehumidification requirements). For simplicity, these bases will be identified as Northern AFB, Central AFB, and Southern AFB. Decision-makers or proxy decision-makers at three Air Force bases in these regions were contacted and asked to weight the model and generate alternatives. Their inputs were based on the generic multi-zone office facility (6500 SF)

shown in Figure 26. Detailed characteristics of the generic facility are provided in Appendix B.

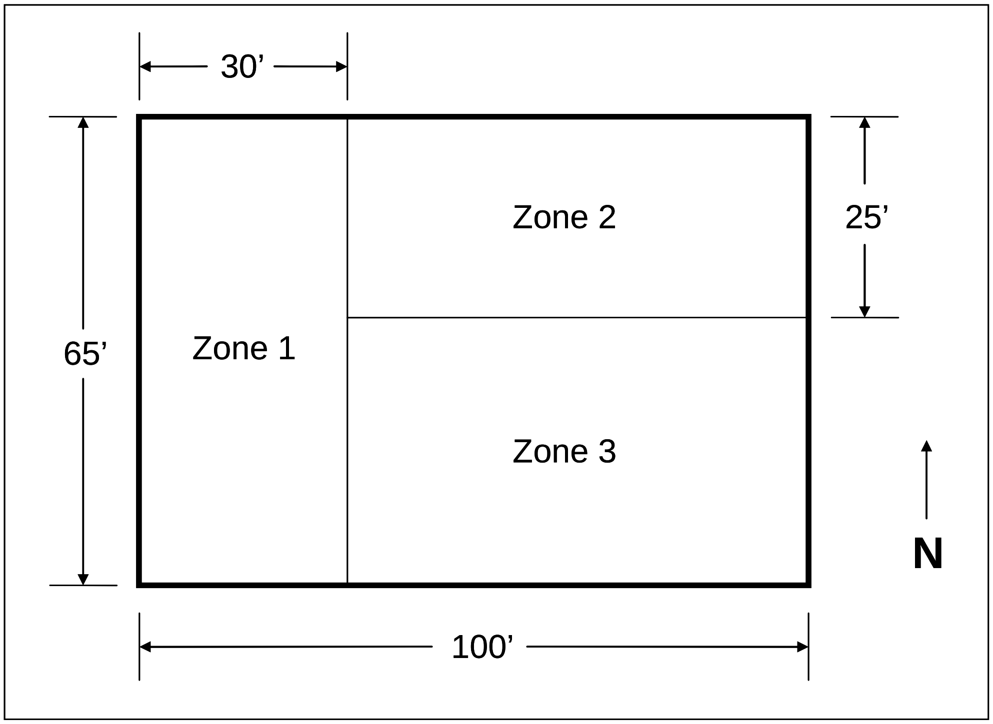


Figure 26. Layout of Generic Office Building

Step Five: Weight Value Hierarchy

The weighting of the hierarchy accounts for the differing levels of importance of each of the evaluation measures. Each of the decision-makers assigned weights to the model based on their base’s preferences, rather than their own preferences. In addition, the weights were assigned using the local weighting process presented in Chapter 2.

There are a number of methods for weighting a value hierarchy, regardless of whether the local or global weighting process is utilized. In a simple example, the decision-maker could be handed 1000 marbles and asked to divide the marbles to signify

the relative importance of each objective or measure. For this research, the weights were assigned using a process known as swing weighting. In this approach, the objectives or measures in a branch are arranged in order of preference from least preferred to most preferred. The least preferred objective or measure is given a weight of x and the remaining objectives or measures are scaled as a multiple of the smallest weight. The weights are then rescaled so that they sum to 1 (Kirkwood, 1997). For example, for the first tier of values (recall that the first tier consists of the *Environmental Impact*, *Operation*, and *Resources* objectives), a decision-maker may select *Operation* as the least preferred. It is given a weight of x. If *Resources* provides twice as much value to the decision-maker than *Operation*, it is given a weight of $2x$. *Environmental Impact* would be scaled in the same manner. Requiring these weights to sum to one creates one equation with one unknown, (the value x) which can be solved to obtain the local weights of the first tier of the hierarchy.

Despite the fact that all three decision-makers considered the same generic facility, they weighted the model differently. The weights of the hierarchy at Northern AFB were relatively balanced, as each of the means objectives was assigned at least 10% of the value. *Cost* was the most important means objective, however, as it accounted for nearly 30% of total value at Northern AFB. At Central AFB, 44% of the value was placed on the *Operation* objective, followed by *Cost* at 22%. Finally, at Southern AFB, the *Operation* objective also had the highest value at 37%, followed by *Cost* at 25%. Table 6 provides the global weights of the value hierarchy at each base.

Table 6. Global Weights of Measures for Each Location

Fundamental Objective	Means Objective	Measure	Northern AFB	Central AFB	Southern AFB
Environmental Impact			**0.294**	**0.156**	**0.185**
	Aesthetics		0.176	0.063	0.074
		Visual Impact	0.106	0.006	0.037
		Noise	0.071	0.057	0.037
	Environmental Stewardship		0.118	0.094	0.111
		Energy Consumption	0.059	0.075	0.074
		Use of Renewable Technology	0.059	0.019	0.037
Operation			**0.412**	**0.625**	**0.556**
	Occupant Comfort		0.176	0.438	0.370
		Supply Air Temp (heating)	0.118	0.328	0.222
		Dehumidification	0.059	0.109	0.148
	Maintainability		0.235	0.188	0.185
		Location of Equipment	0.105	0.134	0.101
		Available Materials	0.052	0.027	0.051
		Available Service	0.078	0.027	0.034
Resources			**0.294**	**0.219**	**0.259**
	Cost		0.294	0.219	0.259
		Initial Cost	0.176	0.044	0.120
		O&M Cost	0.059	0.146	0.100
		Replacement Cost	0.059	0.029	0.040

Step Six: Alternative Generation

The conventional HVAC alternatives that were selected for evaluation were based on the typical HVAC systems used for this type of facility. Recall from Chapter 2 that packaged air-conditioners (rooftop units) and chillers make up 80% of the HVAC systems used for commercial facilities. For this research, a single-zone rooftop system (one unit for each zone), a multizone rooftop unit, and a water-cooled chiller variable air volume (VAV) system were selected as the conventional alternatives. The heating systems that were selected were based on the inputs of the decision-makers. At Northern AFB, an electric hot water boiler was specified. Central AFB uses natural gas furnaces, while Southern AFB typically installs natural gas hot water boilers for this type of facility.

For a number of reasons, only one GSHP alternative, a vertical closed-loop GSHP, was considered. Horizontal closed-loop systems require more land area (which may or may not be available) than vertical closed-loop systems and are better suited for small applications, such as residential projects. Open-loop systems require a large source of water, which may not be available in all locations. In addition, groundwater regulations may limit or prohibit the use of available water sources. Because of the risk of leaking refrigerant, few states allow the use of direct expansion GSHP systems.

Having selected the alternatives for evaluation, the scoring and analysis of alternatives was conducted at each of the three locations. Chapter 4 presents the results of this analysis.

IV. Analysis

Overview

This chapter covers Steps Seven, Eight, and Nine of the ten-step value-focused thinking (VFT) process. In Step Seven, the results of the alternative scoring are presented. In Step Eight, a deterministic analysis of the value scores is performed. Finally, in Step Nine, sensitivity analysis of the value model is accomplished to analyze the impact of changing evaluation weights on the alternative rankings. Because this research was conducted for three different locations, the results of Steps Seven, Eight, and Nine are presented separately for each installation.

Northern AFB

The following sections cover the scoring and analysis of alternatives at Northern AFB. Relevant project information for Northern AFB is presented in Table 7.

Table 7. Project Information for Northern AFB

Design Characteristic	Information
Summer Design Dry Bulb	89 F
Summer Design Wet Bulb	67 F
Summer Setpoint Temp	75 F
Winter Design Dry Bulb	-20 F
Winter Setpoint Temp	70 F
Design Simulation Period	Jan - Dec

Step Seven: Alternative Scoring at Northern AFB

In order to score the alternatives, data for each evaluation measure was collected or calculated. For this research, a number of different sources were utilized for the data collection process. Trace™ 700, a comprehensive building analysis program made by Trane, was used to determine the energy consumption and the heating and cooling loads for each alternative. Cost data was derived from the *RS Means Mechanical Cost Data* book (Mossman, 2004) and the *ASHRAE Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings* manual (Kavanaugh and Rafferty, 1997). HVAC equipment performance data was obtained from various manufacturers' product catalogs and the *ASHRAE Ground Source Heat Pump* manual. Data for two of the categorical evaluation measures, Noise and Visual Impact, were randomly generated using Microsoft Excel's random function. Unfortunately, data for Noise and Visual Impact can only be determined from interviews with a building's occupants due to the subjective nature of these measures. Since the building in this research is generic, random generation was chosen as an appropriate data collection methodology. The proxy decision-maker at each base provided data for the remaining categorical evaluation measures. Finally, Logical Decisions® for Windows, a decision analysis software suite, was used for the actual scoring and sensitivity analysis. A detailed analysis of the equations, definitions and data sources used to score the alternatives is provided in Appendix A. Table 8 presents the final data for each of the four alternatives at Northern AFB.

Table 8. Data for Alternatives at Northern AFB

Measure	Chiller/Tower with VAV	MZ Rooftop	SZ Rooftop	GSHP
Initial Cost ($)	$80,260.00	$80,250.00	$51,339.00	$61,269.08
O&M Cost ($)	$3,956.99	$4,237.74	$4,228.02	$1,630.70
Replacement Cost ($)	$21,171.63	$35,787.24	$22,894.47	$7,352.03
Energy Consumption (kwh)	62055.25102	91953.49	91593.14	40101.30
Use of Renewable Technology	None	None	None	Renewable
Visual Impact	Neutral	Unobtrusive	Unobtrusive	Unobtrusive
Noise	Neutral	Imperceptible	Imperceptible	Imperceptible
Supply Air Temp (heating) (deg F)	95	95	95	86.3
Dehumidification	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year
Location of Equipment	Outdoors/Easily Accessible	Outdoors/Difficult to Access	Outdoors/Difficult to Access	Indoor/Easy
Available Materials	50 Miles or More	50 Miles or More	50 Miles or More	50 Miles or More
Available Service	Within 50 Miles	Within 50 Miles	Within 50 Miles	Within 50 Miles

Having collected the data, the alternatives were scored using a particular value function known as the additive value function. Although there are other value functions that can be used to rank alternatives, the additive value function is advantageous because it is easily understood and allows for sensitivity analysis (Shoviak, 2001). The additive value function requires that each evaluation measure is assigned a single dimension value function $v_i(x_i)$ and that each single dimension value function is assigned a weight λ_i. Recall from Step Four that SDVFs convert the score of a measure into a unitless value between 0 (least preferred) and 1 (most preferred). Given that the measures are assigned a SDVF and a weight, the value function of each evaluation measure is the product of its SDVF value and its weight. As seen in Equation 3, the additive value function is the weighted sum of each evaluation measure's value function (Kirkwood, 1997).

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i) \tag{3}$$

where

$v(x)$ = the total value score of alternative x

$v_i(x_i)$ = the single dimension value function for measure i

x_i = the score for alternative x on measure i

λ_i = the scaling constant or weight for measure i

n = the total number of measures

$$\sum_{i=1}^{n} \lambda_i = 1$$

Using the additive value function, an alternative with optimal scores in each evaluation measure would receive an overall value score of 1. Conversely, an alternative that scores the minimum score in each evaluation measure would receive an overall value of 0. The final results of the alternative scoring at Northern AFB are presented in Figure 27. Overall, the ground-source heat pump (GSHP) alternative was the most preferred, capturing 0.804 of the decision-maker's total value. The single zone (SZ) rooftop unit system scored 0.727 of the total value, followed by the chiller/VAV system with 0.633 of the total value. The multizone (MZ) rooftop unit was the least preferred alternative, achieving only 0.596 of the total value.

Alternative	Value
GSHP	0.804
Single Zone Rooftop Unit with Hot Water Boiler	0.727
Chilled Water/VAV with Hot Water Boiler	0.633
Multizone Rooftop Unit with Hot Water Boiler	0.596

Figure 27. Total Value Scores for Alternatives at Northern AFB

Step Eight: Deterministic Analysis at Northern AFB

The underlying mathematical equation of the additive value function allows for detailed deterministic analysis. Because the overall value score for an alternative is obtained from the weighted sum of its measures, the contribution of each measure to the overall score can be analyzed to provide further insight into the performance of alternatives (Weir, 2004). Specifically, the decision-maker gains insight into the strengths and weaknesses of each alternative and can investigate why a particular alternative is preferred or not preferred.

Figure 28 shows the contribution of the fundamental objectives to the overall value scores at Northern AFB. The most preferred alternative, the GSHP system, scored much higher in the *Resources* and *Environmental Impact* objectives than the other alternatives. However, the GSHP's low score in the *Operation* objective warrants further investigation.

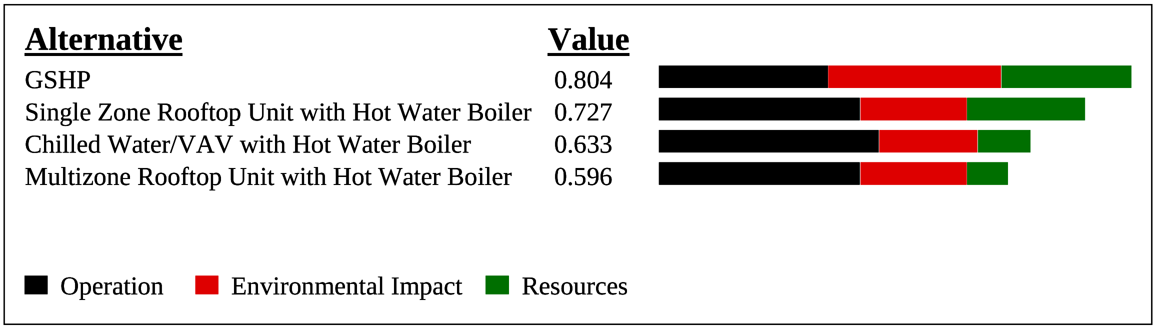


Figure 28. Contribution of Fundamental Objectives to Overall Value Scores at Northern AFB

Figure 29 shows the contribution of each evaluation measure to the overall value scores. By default, Logical Decisions® presents the evaluation measures from the measure with the highest global weight to the measure with the lowest global weight.

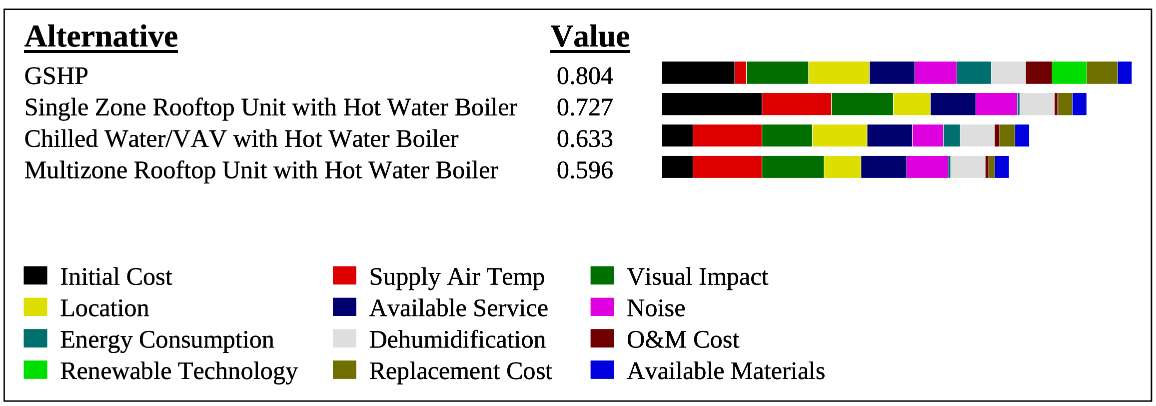


Figure 29. Contribution of Evaluation Measures to Overall Value Scores at Northern AFB

From this perspective, it is easy to see the strengths and weaknesses of each of the alternatives. The GSHP's low score in the *Operation* objective is due to its low score in

the Supply Air Temperature measure. This illustrates one of the shortcomings of GSHPs. Because conventional systems use dedicated heating equipment, the heating equipment is sized separately from the cooling equipment, which enables the design engineer to specify supply air that would be considered thermally comfortable. Rooftop units are often packaged with heating functions, but the heating capacity of rooftop units is typically sufficient to supply thermally comfortable air. For example, the peak cooling and heating loads of the generic office building at Northern AFB are given in Table 9. According to *RS Means*, 4-ton SZ rooftop units with natural gas heating have a heating capacity of 95,000 British Thermal Units per hour (BTU/hr), more than double the required capacity of Rooms 1 and 2. In Room 3, a 6-ton SZ rooftop unit would be specified, which has a heating capacity of 140,000 BTU/hr. If a 15-ton MZ rooftop unit was utilized for all three rooms, it would have a heating capacity of 360,000 BTU/hr, more than twice the required heating load of the building (Mossman, 2004).

Table 9. Peak Cooling and Heating Loads at Northern AFB

	Cooling Loads BTU/hr	Cooling Loads Tons	Heating Loads BTU/hr
Room 1	48071	4.01	45876
Room 2	40465	3.37	46138
Room 3	73380	6.12	62807
Overall	161916	13.49	154821

Unlike conventional systems, GSHPs use the same equipment for both heating and cooling. Thus, GSHPs typically have much lower heating capacities than rooftop units. For example, according to the *Trane High Efficiency Horizontal and Vertical Water-Source Comfort System* product catalog, a 4.36-ton water-source heat pump has a

heating capacity of 35,100 BTU/hr (assuming an entering water temperature of 32F). Although this water-source heat pump has sufficient cooling capacity for Rooms 1 and 2, it lacks the capacity to meet the peak heating loads. Consequently, the warmth of the supply air temperature is reduced.

Another method of gaining insight into the performance of alternatives is to examine the actual and effective weights of the evaluation measures. The actual weight is the assigned weight given to a measure by the decision-maker. The effective weight is what the weight of a measure would be if the projected range of a measure equaled the actual observed range of the alternatives. For example, consider a hypothetical measure, Measure Z, which is assigned an actual weight of 40%. This suggests that Measure Z will have a substantial impact on the overall value scores for alternatives. However, if all the alternatives have the same score for Measure Z, then Measure Z has no impact on the rankings of alternatives. Essentially, the effective weight of Measure Z is zero.

Table 10 provides the actual and effective weights of the evaluation measures at Northern AFB. Four of the measures (Initial Cost, Supply Air Temperature, Visual Impact, and Location) had actual weights above 10% and together accounted for 50% of the overall value. Thus, the HVAC designer should ensure that the alternatives' scores for these evaluation measures are accurate. In terms of effective weights, four measures (Initial Cost, Supply Air Temperature, Energy Consumption, and Renewable Technology) had effective weights above 10% and together accounted for 67% of the ranking of alternatives at Northern AFB.

Table 10. Actual and Effective Weights of Evaluation Measures at Northern AFB

Evaluation Measure	Actual Weight	Effective Weight
Initial Cost	17.70%	23.90%
Supply Air Temp (heating)	11.80%	19.88%
Visual Impact	10.60%	4.34%
Location	10.50%	8.58%
Available Service	7.80%	0.00%
Noise	7.10%	3.62%
Dehumidification	5.90%	0.00%
Energy Consumption	5.90%	11.08%
O&M Cost	5.90%	7.79%
Renewable Technology	5.90%	12.06%
Replacement Cost	5.90%	8.76%
Available Materials	5.20%	0.00%

Step Nine: Sensitivity Analysis at Northern AFB

When scoring alternatives, two assumptions are made. First, it is assumed that the weights of the evaluation measures are accurate and will not change for the given decision. Second, it is assumed that the SDVFs accurately reflect the increasing or decreasing returns to scale of the decision-maker and will not change for the given decision. If these assumptions are true, the decision-maker can be confident that the overall value scores reflect the values and objectives of the decision-maker.

However, it is often insightful to conduct sensitivity analysis to examine the impact on the ranking of alternatives based on changes to the scoring assumptions. For instance, sensitivity analysis may be useful if the individual building the model is only a proxy for the actual decision-maker. Although sensitivity analysis can be conducted on either of the two assumptions, it is impractical to conduct sensitivity analysis on the SDVFs because they typically will not change enough to impact the ranking of

alternatives. Thus, sensitivity analysis is only accomplished on the model's weights (Weir, 2004).

When dealing with weights, the sensitivity analysis methodology is fairly straightforward. The weight of one value or measure is varied from 0 to 1, while the other dependent weights are changed proportionally. The overall value scores for alternatives are recalculated at each varying weight, and the results are then graphed on a breakeven chart (Weir, 2004). A value or measure is classified as sensitive if the ranking of alternatives changes within a realistic change in weight. If a value or measure is sensitive, the decision-maker can expend resources to ensure that the original assigned weight is accurate. Conversely, if the model is found to be insensitive to changing weights, then the decision-maker can be confident that the ranking of alternatives accurately reflects the decision-maker's values.

For this research, sensitivity analysis was first conducted on the first-tier fundamental objectives. If an objective was found to be sensitive, sensitivity analysis was conducted on its means objectives. This process was repeated until no further insight was obtained.

Sensitivity Analysis of Environmental Impact Objective at Northern AFB

The *Environmental Impact* fundamental objective showed little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 30. Currently, this objective accounts for 29.4% of the overall value of alternatives, as depicted by the vertical line in Figure 30. The GSHP alternative remains the most preferred alternative until the objective's weight is approximately 12%. At that point, the

SZ rooftop unit system becomes the most preferred. The MZ rooftop unit becomes the third most preferred alternative when the objective's weight is approximately 60%. Interestingly, when the weight of the *Environmental Impact* objective is zero, the GSHP system is still the second most preferred alternative. This suggests that GSHPs are a viable option at Northern AFB even in situations where the base has little concern for energy consumption or aesthetics.

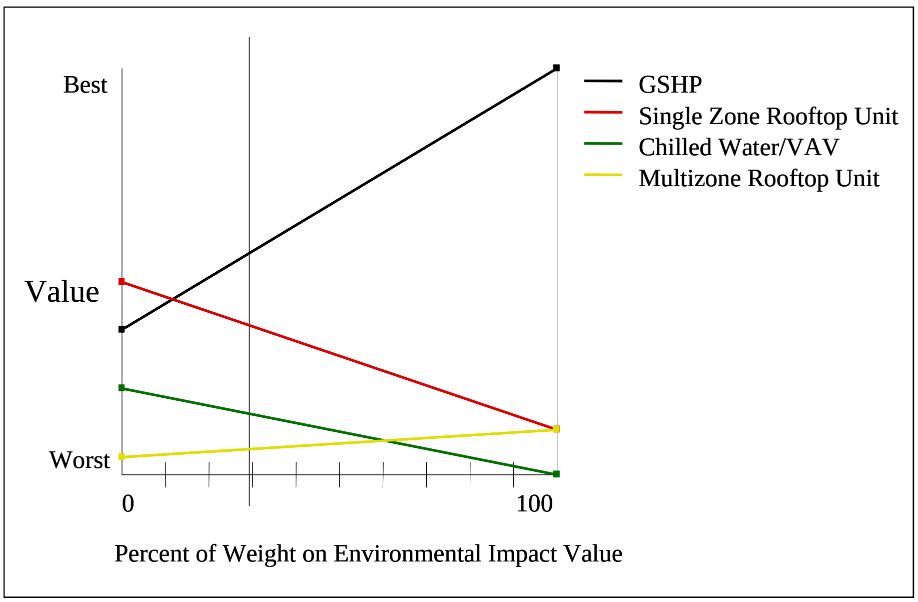


Figure 30. Sensitivity Analysis of Environmental Impact Objective at Northern AFB

Sensitivity Analysis of Operation Objective at Northern AFB

The *Operation* fundamental objective also showed little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 31. The *Operation* objective is currently assigned a weight of 41.2%. The GSHP alternative remains the most preferred alternative until the weight is approximately 63%. At that point, the SZ

rooftop unit system becomes the most preferred alternative. At 72%, the chiller/VAV system overtakes the SZ system as the most preferred. Note that the GSHP would be the least preferred alternative if the *Operation* objective was the only objective that was considered. This suggests that at Northern AFB, conventional HVAC options or modified GSHP systems would be preferred for buildings with very strict HVAC requirements.

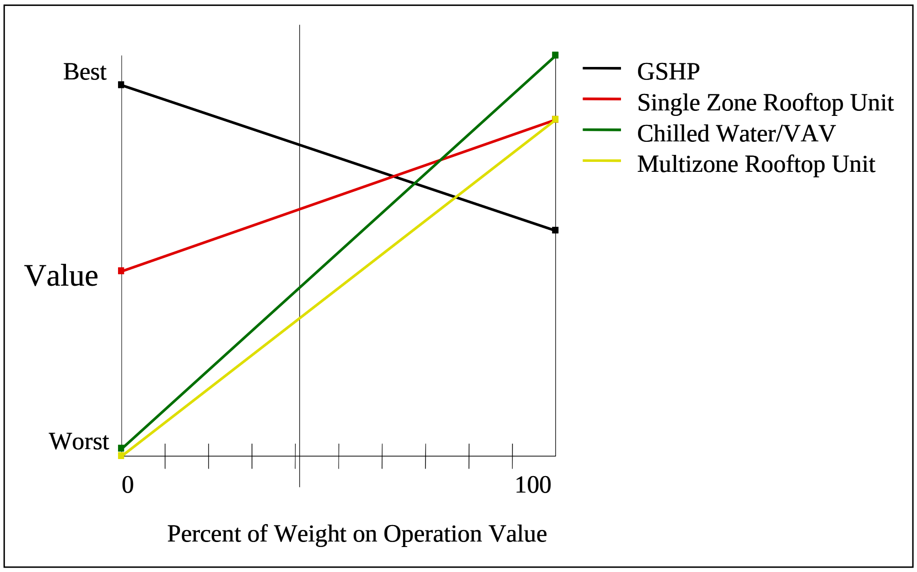


Figure 31. Sensitivity Analysis of Operation Objective at Northern AFB

<u>Sensitivity Analysis of Resources Objective at Northern AFB</u>

The final fundamental objective, *Resources*, showed almost no sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 32. This objective currently accounts for 29.4% of the overall value of alternatives. At Northern AFB, the GSHP alternative remains the most preferred alternative, regardless of the

objective's weights. The only change in rankings occurs at 7%, when the SZ rooftop unit system moves from the third most preferred alternative to the second most preferred.

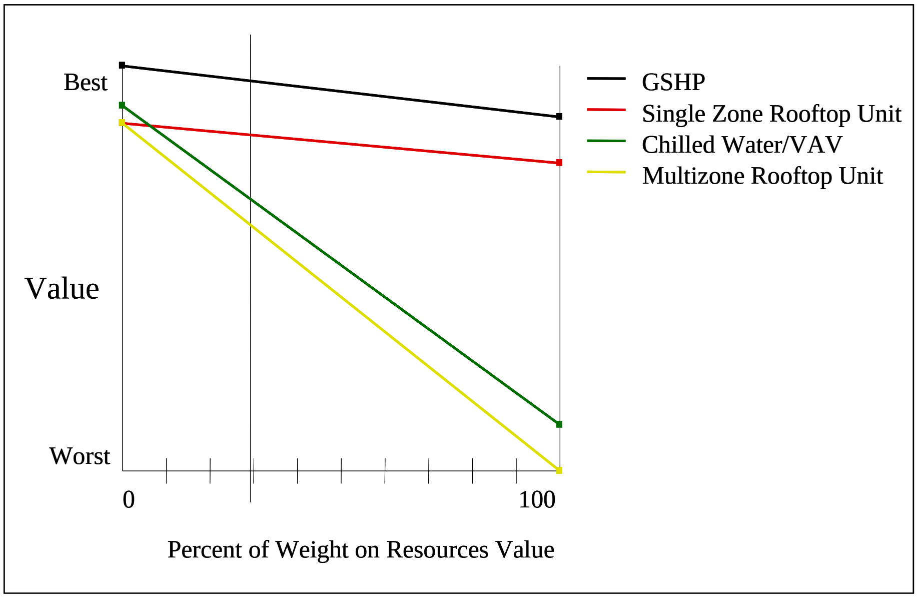


Figure 32. Sensitivity Analysis of Resources Objective at Northern AFB

Overall Sensitivity Comments of the Value Model for Northern AFB

Table 11 provides a summary of the current weights and required adjusted weights of each of the fundamental objectives. The adjusted weight represents the weight at which the most preferred alternative changes from the GSHP alternative to another alternative. Based on the required adjusted weights, it is reasonable to conclude that the value model at Northern AFB is insensitive to changing weights. The *Resources* fundamental objective was insensitive, while the other two required percent changes in weight of over 50%. Thus, no further sensitivity analysis of the model was warranted.

Table 11. Required Adjusted Weight of Fundamental Objectives at Northern AFB

Fundamental Objective	Current Global Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Environmental Impact	29.40%	12.00%	-59.18%	SZ Rooftop
Operation	41.20%	63.00%	52.91%	SZ Rooftop
Resources	29.40%	Insensitive		

Central AFB

The following sections cover the scoring and analysis of alternatives at Central AFB. Relevant project information for Central AFB is presented in Table 12

Table 12. Project Information for Central AFB

Design Characteristic	Information
Summer Design Dry Bulb	92 F
Summer Design Wet Bulb	78 F
Summer Setpoint Temp	78 F
Winter Design Dry Bulb	4 F
Winter Setpoint Temp	68 F
Design Simulation Period	Jan - Dec

Step Seven: Alternative Scoring at Central AFB

Table 13 presents the final data for each of the four alternatives at Central AFB.

Table 13. Data for the Alternatives at Central AFB

Measure	Chiller/Tower VAV	MZ Rooftop	SZ Rooftop	GSHP
Initial Cost ($)	$76,170.00	$81,500.00	$50,119.50	$67,137.43
O&M Cost ($)	$3,647.10	$3,640.64	$3,612.64	$1,324.13
Replacement Cost ($)	$19,912.37	$36,344.67	$22,350.64	$7,664.50
Energy Consumption (kwh)	24141.44	31547.64	30881.63	18524.29
Use of Renewable Resources	None	None	None	Renewable Energy System
Visual Impact	Obtrusive	Neutral	Unobtrusive	Unobtrusive
Noise	Noticeable	Imperceptible	Noticeable	Imperceptible
Supply Air Temp (heating) (deg F)	95	95	95	92.9
Dehumidification	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 98% of the Year
Location of Equipment	Outdoors/Easily Accessible	Outdoors/Difficult to Access	Outdoors/Difficult to Access	Indoors/Easy Accessible
Available Materials	Within 50 Miles	Within 50 Miles	Within 50 Miles	Within 50 Miles
Available Service	Within 50 Miles	Within 50 Miles	Within 50 Miles	Within 50 Miles

The final results of the alternative scoring at Central AFB are presented in Figure 33. Overall, the GSHP alternative was the most preferred, capturing 0.813 of the total value. The chiller/VAV system achieved 0.741 of the total value, followed by the SZ rooftop unit system at 0.712 of the total value. Finally, the multizone (MZ) rooftop unit was the least preferred alterative, attaining 0.697 of the total value.

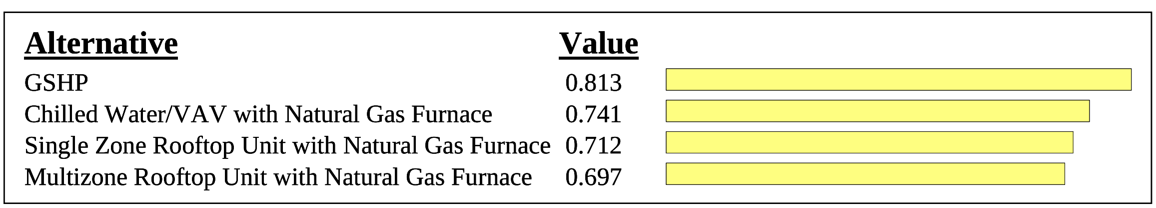


Figure 33. Total Value Scores for Alternatives at Central AFB

Step Eight: Deterministic Analysis at Central AFB

Figure 34 shows the contribution of the fundamental objectives to the overall value scores at Central AFB. The results are very similar to those at Northern AFB. The GSHP system scored much higher in the *Resources* and *Environmental Impact* objectives than the other alternatives, but achieved a lower score in the *Operation* objective.

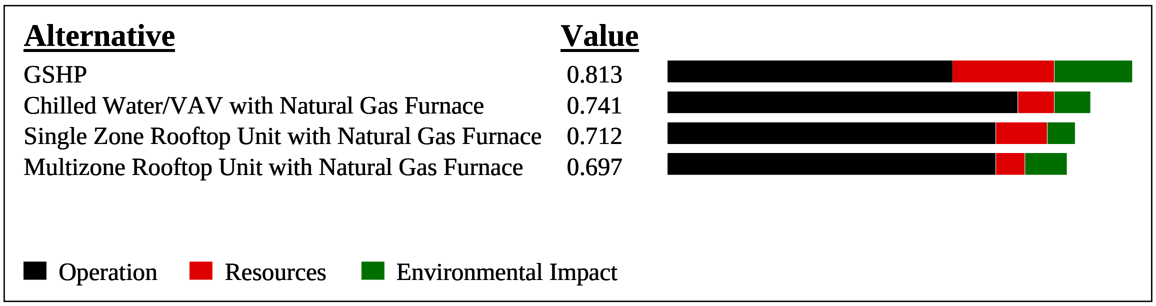


Figure 34. Contribution of Fundamental Objectives to Overall Value Scores at Central AFB

Figure 35 shows the contribution of each of the evaluation measures to the overall value scores. Once again, the GSHP lost ground in the Supply Air Temperature measure, which is not unexpected considering the earlier discussion about the heating capacity of GSHPs. The GSHP makes up for this measure by scoring higher in the O&M Cost, Energy Consumption, Replacement Cost, and Use of Renewable Technology measures.

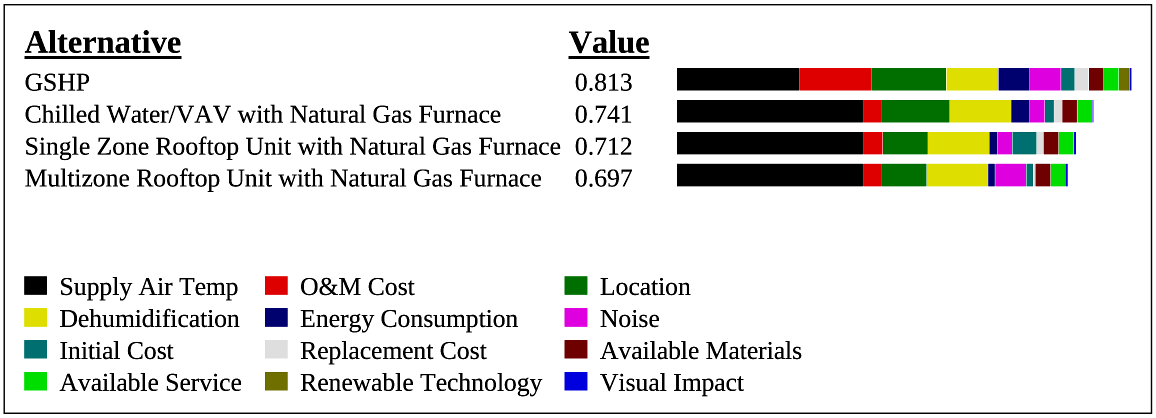


Figure 35. Contribution of Evaluation Measures to Overall Value Scores at Central AFB

Table 14 provides the actual and effective weights of the evaluation measures at Central AFB. Four measures (Supply Air Temperature, O&M Cost, Location, and Dehumidification) dominated the weighting of the value model. Together, they accounted for over 70% of the total value score. Given limited resources, HVAC designers at Central AFB should focus their energy on ensuring the accuracy of the data for these measures.

It is insightful to note that the O&M Cost measure had nearly the same effective weight as the Supply Air Temperature measure. At the same time, the Dehumidification measure, which had a high actual weight, had little impact on the ranking of alternatives. Although the Supply Air Temperature and Dehumidification measures account for 43% of the actual value of the model, their effective weights sum to 30%. This explains, in part, why the GSHP is the most preferred alternative, despite its relatively poor performance in those two measures.

Table 14. Actual and Effective Weights of Evaluation Measures at Central AFB

Evaluation Measure	Actual Weight	Effective Weight
Supply Air Temp (heating)	32.80%	26.52%
O&M Cost	14.60%	22.36%
Location	13.40%	12.74%
Dehumidification	10.90%	3.90%
Energy Consumption	7.50%	10.09%
Noise	5.70%	6.75%
Initial Cost	4.40%	7.48%
Replacement Cost	2.90%	5.02%
Available Materials	2.70%	0.00%
Available Service	2.70%	0.00%
Renewable Technology	1.90%	4.47%
Visual Impact	0.60%	0.68%

Step Nine: Sensitivity Analysis at Central AFB

Sensitivity analysis was first conducted on the first-tier fundamental objectives. If an objective was found to be sensitive, sensitivity analysis was conducted on its means objectives. This process was repeated until no further insight was obtained.

<u>Sensitivity Analysis of Environmental Impact Objective at Central AFB</u>

The *Environmental Impact* fundamental objective showed little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 36. This objective currently accounts for 15.6% of the overall value of alternatives at Central AFB. The GSHP alternative remains the most preferred alternative until the objective's weight is approximately 0%, while the MZ rooftop unit becomes the third and second preferred alternative when the objective's weight is approximately 22% and 50%, respectively. Similar to the results at Northern AFB, the GSHP system is still a viable option at Central AFB even when the weight of this objective is 0%.

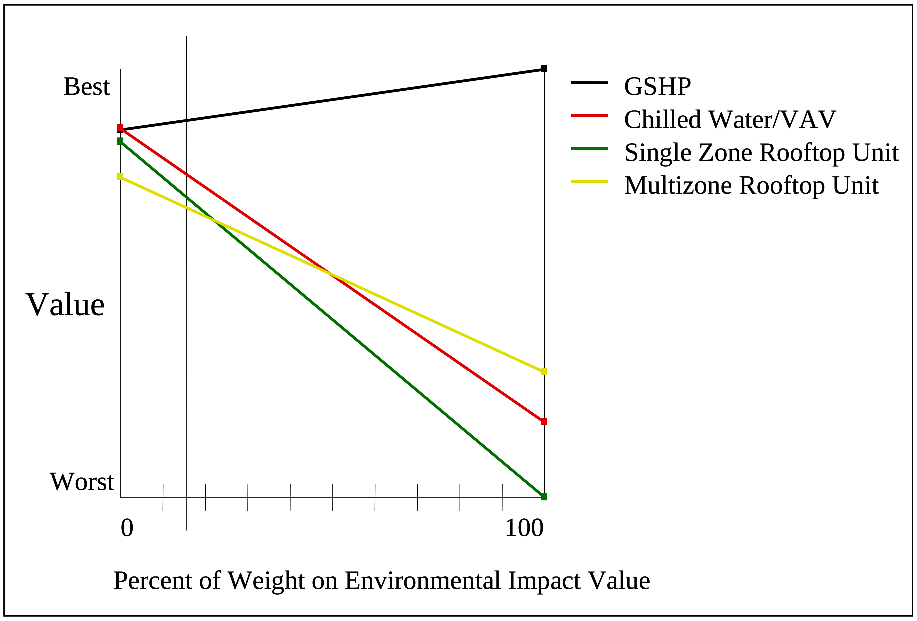


Figure 36. Sensitivity Analysis of Environmental Impact Objective at Central AFB

Sensitivity Analysis of Operation Objective at Central AFB

The *Operation* fundamental objective showed little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 37. This objective is currently assigned a weight of 62.5%. The GSHP alternative remains the most preferred alternative until the weight is approximately 72%. Among the conventional HVAC options, the only change in ranking occurs at 31% when the chiller/VAV system overtakes the SZ rooftop unit system. Once again, the GSHP would be the least preferred alternative if the *Operation* objective was the only objective that was considered.

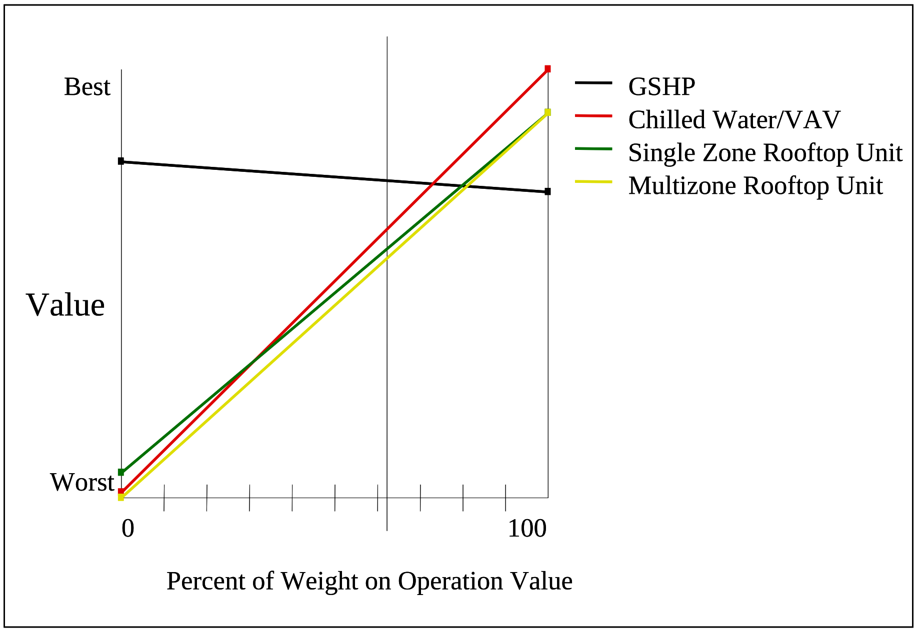


Figure 37. Sensitivity Analysis of Operation Objective at Central AFB

Sensitivity Analysis of Resources Objective at Central AFB

The final fundamental objective, *Resources*, also shows very little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 38. Currently, the *Resources* objective accounts for 21.9% of the overall value of alternatives. The GSHP alternative remains the most preferred alternative until the objective's weight is approximately 10%. In addition, the overall value score of the GSHP alternative varies the least with changing weights of this objective. The SZ rooftop unit system, which is currently the third preferred alternative, becomes the least and second preferred alternative when the objective's weight is approximately 15% and 38%, respectively.

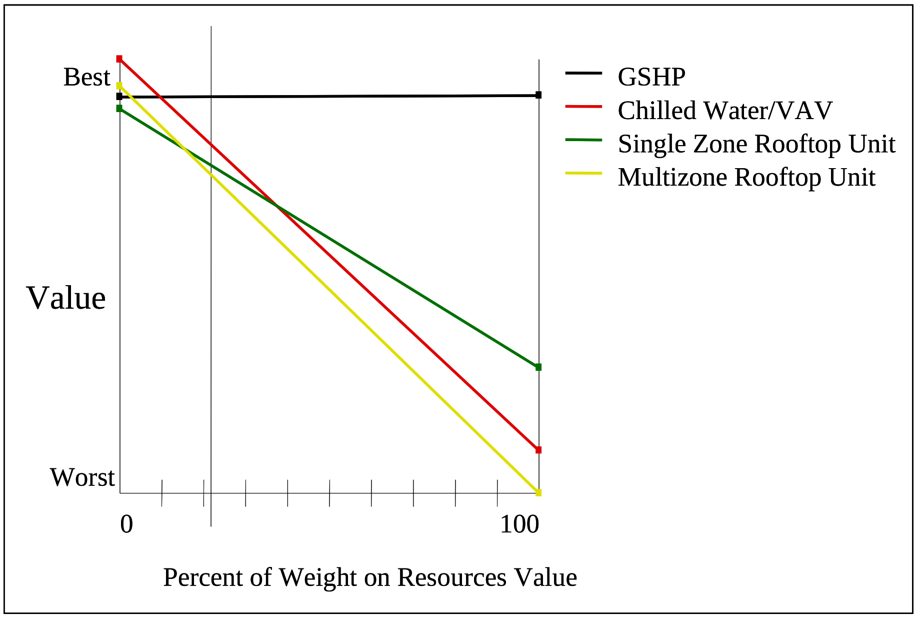


Figure 38. Sensitivity Analysis of Resources Objective at Central AFB

Overall Sensitivity Comments of the Value Model for Central AFB

Table 15 provides a summary of the current weights and required adjusted weights of each of the fundamental objectives. Like Northern AFB, the value model is fairly insensitive to changing weights. Both the *Environmental Impact* and *Resources* objectives require percent changes of over 100% to change the most preferred alternative. The *Operation* objective only requires a 15% increase, but it already has the highest weight of the three objectives and is more likely to decrease than increase. Overall, the value model is insensitive and further sensitivity analysis is unneeded.

Table 15. Required Adjusted Weight of Fundamental Objectives at Central AFB

Fundamental Objective	Current Global Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Environmental Impact	15.63%	0.00%	-100.00%	Chiller/VAV
Operation	62.50%	72.00%	15.20%	Chiller/VAV
Resources	21.88%	10.00%	-118.75%	Chiller/VAV

Southern AFB

The following sections cover the scoring and analysis of alternatives at Southern AFB. Relevant project information for Southern AFB is presented in Table 16.

Table 16. Project Information for Southern AFB

Design Characteristic	Information
Summer Design Dry Bulb	90 F
Summer Design Wet Bulb	77 F
Summer Setpoint Temp	78 F
Winter Design Dry Bulb	33 F
Winter Setpoint Temp	68 F
Design Simulation Period	Jan - Dec

Step Seven: Alternative Scoring at Southern AFB

The final data used to score alternatives at Southern AFB is presented in Table 17.

Table 17. Data for the Alternatives at Southern AFB

Measure	Chiller/Tower VAV	MZ Rooftop	SZ Rooftop	GSHP
Initial Cost ($)	$76,854.00	$84,000.00	$50,164.30	$72,218.32
O&M Cost ($)	$3,364.68	$3,190.08	$3,130.78	$1,317.94
Replacement Cost ($)	$20,252.15	$37,459.54	$22,370.61	$7,664.50
Energy Consumption (kwh)	20432.48	26724.43	25589.67	14722.56
Use of Renewable Resources	None	None	None	Renewable Energy System
Visual Impact	Neutral	Neutral	Neutral	Unobtrusive
Noise	Noticeable	Imperceptible	Imperceptible	Imperceptible
Supply Air Temp (heating) (deg F)	95	95	95	95
Dehumidification	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 100% of the Year	Meets Requirements 98% of the Year
Location of Equipment	Outdoors/Easily Accessible	Outdoors/Difficult to Access	Outdoors/Difficult to Access	Indoors/Easy Accessible
Available Materials	Within 50 Miles	Within 50 Miles	Within 50 Miles	Within 50 Miles
Available Service	Within 50 Miles	Within 50 Miles	Within 50 Miles	Within 50 Miles

The results of the alternative scoring at Southern AFB are presented in Figure 39. Once again, the GSHP alternative was the most preferred at 0.873 of the total value. The chiller/VAV system captured 0.764 of the total value, followed by the SZ rooftop unit system at 0.714 of the total value. The multizone (MZ) rooftop unit was the least preferred alterative, attaining 0.657 of the total value.

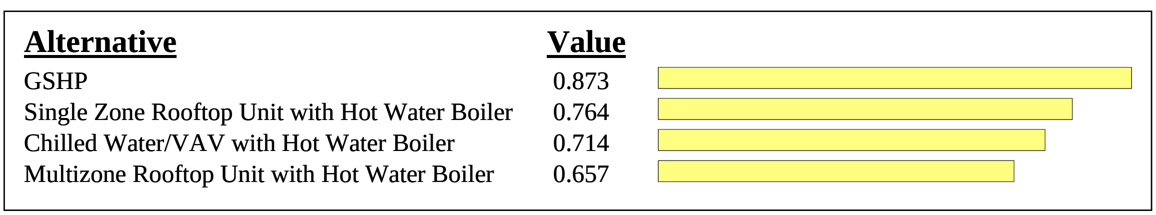


Figure 39. Total Value Scores for Alternatives at Southern AFB

Step Eight: Deterministic Analysis at Southern AFB

Figure 40 shows the contribution of the fundamental objectives to the overall value scores at Southern AFB. Unlike the results at the other two bases, the conventional HVAC systems did not have an advantage over the GSHP in the *Operation* objective. At the same time, the GSHP maintained its advantages in the *Resources* and *Environmental Impact* objectives. This suggests that at Southern AFB, there is little tradeoff involved with using GSHPs.

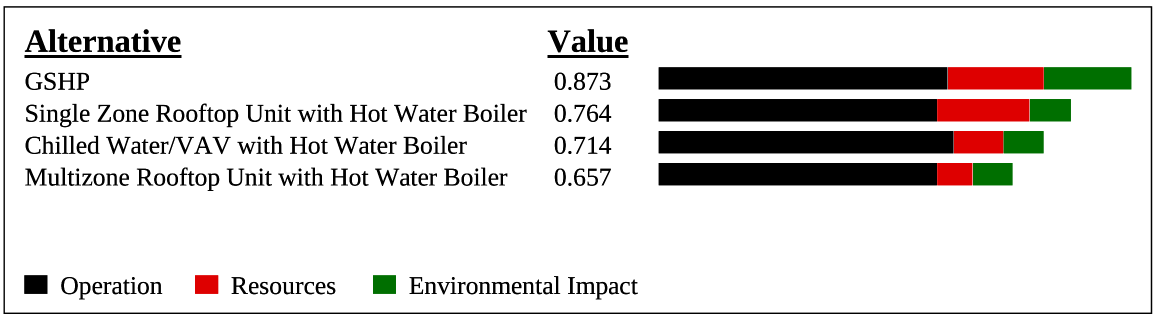


Figure 40. Contribution of Fundamental Objectives to Overall Value Scores at Southern AFB

To further analyze the performance of alternatives, Figure 41 shows the contribution of each evaluation measures to the overall value scores. From this perspective, it is clear why the GSHP does not lose ground in the *Operation* objective. Because of the mild winters at Southern AFB, the GSHP had sufficient capacity to supply thermally comfortable air. Overall, the GSHP has few weaknesses at Southern AFB, except for Initial Cost, which is typically a low scoring measure for GSHPs at any location.

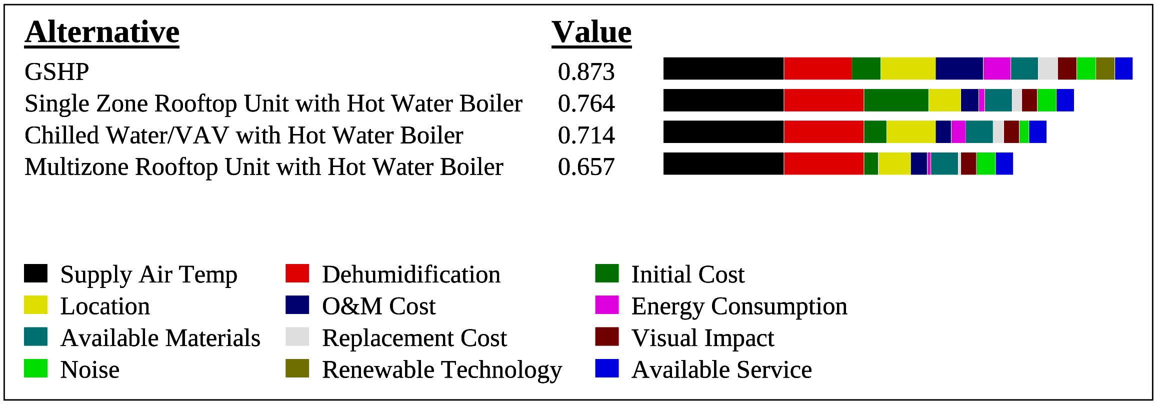


Figure 41. Contribution of Evaluation Measures to Overall Value Scores at Southern AFB

Table 18 provides the actual and effective weights of the evaluation measures at Southern AFB. It is insightful to note that the measure with the highest actual weight, the Supply Air Temperature measure, had an effective weight of 0. Because GSHPs can provide thermally comfortable air at Southern AFB, the conventional systems have no advantage over the GSHP in this measure. Thus, the alternatives all received optimal scores in this measure, resulting in an effective weight of 0.

Overall, four measures (Supply Air Temperature, Dehumidification, Initial Cost, and Location) had actual weights above 10%. Further, five measures (Initial Cost, Location, O&M Cost, Energy Consumption, and Use of Renewable Technology) had effective weights above 10%. These measures should be carefully calculated when scoring alternatives to ensure the rankings truly reflect the values of the decision-maker at Southern AFB.

Table 18. Actual and Effective Weights of Evaluation Measures at Southern AFB

Evaluation Measure	Actual Weight	Effective Weight
Supply Air Temp (heating)	22.22%	0.00%
Dehumidification	14.81%	6.40%
Initial Cost	11.97%	26.20%
Location	10.10%	11.65%
O&M Cost	9.97%	16.90%
Energy Consumption	7.41%	12.22%
Available Materials	5.05%	0.00%
Replacement Cost	3.99%	8.51%
Renewable Technology	3.70%	10.67%
Noise	3.70%	5.33%
Visual Impact	3.70%	2.13%
Available Service	3.37%	0.00%

Step Nine: Sensitivity Analysis at Southern AFB

Like the other two bases, sensitivity analysis was first conducted on the first-tier fundamental objectives. If an objective was found to be sensitive, sensitivity analysis was conducted on its means objectives. This process was repeated until no further insight was obtained.

<u>Sensitivity Analysis of Environmental Impact Objective at Southern AFB</u>

The *Environmental Impact* fundamental objective showed no sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 42. The *Environmental Impact* objective currently accounts for 18.5% of the overall value of alternatives. Regardless of the weight of the *Environmental Impact* Value, there is no change in the ranking of alternatives.

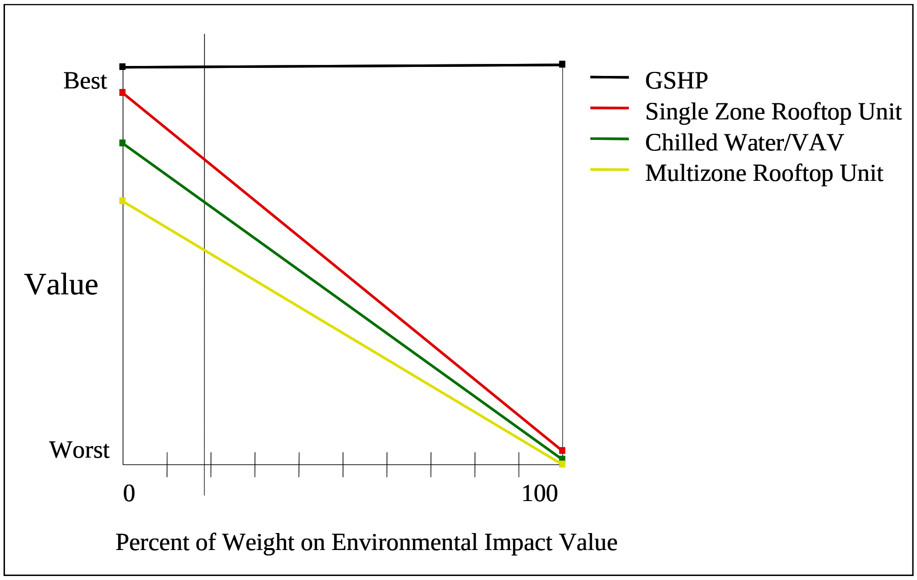


Figure 42. Sensitivity Analysis of Environmental Impact Objective at Southern AFB

Sensitivity Analysis of Operation Objective at Southern AFB

The *Operation* fundamental showed little sensitivity to changing weights unless this objective dominates the decision problem. The breakeven chart for this objective is provided in Figure 43. This objective is currently assigned a weight of 55.6%. GSHP alternative remains the most preferred alternative until the weight of this objective is approximately 94%. Among the conventional HVAC options, the only change in ranking occurs at 78% when the chiller/VAV system overtakes the SZ rooftop unit system as the second most preferred alternative.

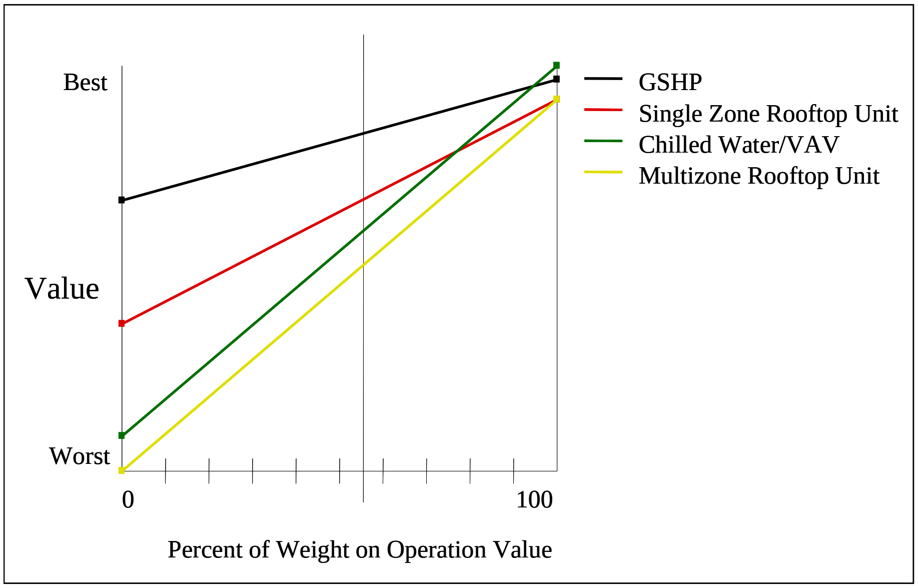


Figure 43. Sensitivity Analysis of Operation Objective at Southern AFB

Sensitivity Analysis of Resources Objective at Southern AFB

The final fundamental objective, *Resources*, showed little sensitivity to changing weights. The breakeven chart for this objective is provided in Figure 44. This objective accounts for 25.9% of the overall value of alternatives. The top alternative, the GSHP, does not change regardless of this objective's weight. The only change in alternative ranking occurs at 11%, when the SZ rooftop unit system becomes the second preferred alternative over the chiller/VAV system.

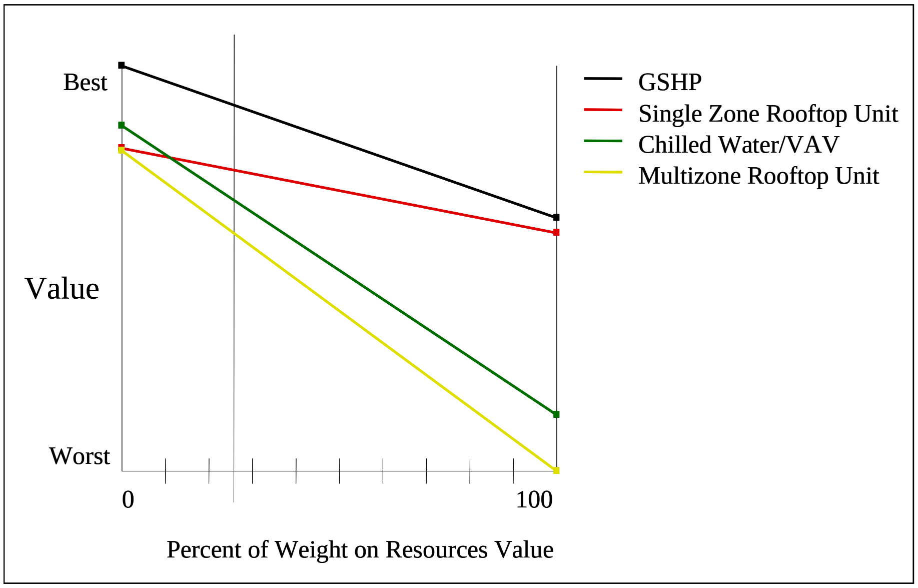


Figure 44. Sensitivity Analysis of Resources Objective at Southern AFB

Overall Sensitivity Comments of the Value Model for Southern AFB

Table 19 provides a summary of the current weights and required adjusted weights of each of the fundamental objectives. Clearly, the value model at Southern AFB is insensitive to changing weights. The GSHP remains the top alternative in both the *Environmental Impact* and *Resources* objectives, regardless of the objectives' weights. The only change to the most preferred alternative occurs in the *Operation* fundamental objective, and it would have to increase by 69% to change the top alternative.

Table 19. Required Adjusted Weight of Fundamental Objectives at Southern AFB

Fundamental Objective	Current Global Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Environmental Impact	18.50%	Insensitive		
Operation	55.60%	94.00%	69.06%	Chiller/VAV
Resources	25.90%	Insensitive		

V. Summary and Conclusions

Overview

This chapter covers the final step of the ten-step value-focused thinking (VFT) process. The research effort is summarized, and the research questions presented in Chapter 1 are addressed. In addition, an overview of the value models benefits and limitations are discussed. Finally, recommendations for future research and final conclusions are covered.

Research Summary

This research effort provides a design tool for military decision-makers that can be used to evaluate the practicality of ground-source heat pumps at military installations. In order to be useful, the design tool had to meet two criteria. First, it had to capture the Air Force's objectives and values regarding its heating, ventilating, and air-conditioning (HVAC) systems. Second, the design tool had to be highly adaptable, given the various locations and climate conditions of the Air Force's installations. The decision-analysis model developed in this research meets those two criteria.

The following research questions guided this research process. The findings for each question are addressed below.

1. Given the various design considerations of HVAC systems, what is the appropriate methodology for HVAC selection?

Because of the competing objectives involved with HVAC selection, value-focused thinking was chosen as the most appropriate methodology. It provides a multi-

objective decision-analysis tool that can be used to compare different HVAC systems. Using the VFT process, the Air Force's values and objectives regarding its HVAC systems are explicitly identified. In addition, the final model is highly adaptable, enabling it to be utilized for various facilities and different locations.

2. What does the Air Force value in terms of their HVAC systems?

The development of the VFT model identified three fundamental values for HVAC systems. First, the Air Force seeks HVAC systems that require minimal resources to install, operate, maintain, and replace. Second, the Air Force desires systems that meet performance requirements. Finally, the Air Force values HVAC systems that have minimal impact on the environment. Under these fundamental values are five objectives that achieve the fundamental values. These objectives include the desire to minimize cost, maximize occupant comfort, utilize highly maintainable systems, be a steward to the environment, and improve aesthetics.

3. How do GSHPs perform in differing regions of the country?

Regardless of location, GSHPs are a viable alternative to conventional HVAC options. At each of the three research locations (North, Central, and Southern), GSHPs were the most preferred alternative. As expected, they performed well in terms of total cost and environmental impact in all three research locations. Further, when environmental impact is not considered, GSHPs are still very competitive with conventional systems.

Value Model Benefits

First and foremost, the primary benefit of this research is the documentation of the Air Force's values concerning its HVAC systems. With the generic value hierarchy, military decision-makers now have a strategic design tool that can be used to compare different HVAC systems. Specifically, the practicality of ground-source heat pumps can be evaluated for any facility at any base. In addition, the groundwork for evaluating future energy-efficient HVAC systems has been completed.

Second, the VFT model utilizes a mathematical approach that is objective, defendable, and repeatable. Because the values and their relative importance are determined before alternatives are considered, there is less risk of bias in the evaluation process. Decision-makers can now clearly articulate why a particular HVAC system is preferred and how well the system meets the organization's objectives.

Third, the VFT model provides valuable insight and allows for great design flexibility. The strengths and weaknesses of different HVAC systems can be evaluated to determine why certain systems are preferred or not preferred. Sensitivity analysis can be conducted to examine the effect of changing evaluation weights. Because the scoring and analysis of alternatives can be conducted before any investment in materials or labor, the design engineer can explore the value of multiple configurations of various systems.

Model Limitations

The validity of the results from this model is heavily dependent on the design engineer. Many of the measures involve work-intensive estimating methods that require

accurate data or realistic assumptions. Obviously, inaccurate data or poor estimating procedures can influence the final ranking of alternatives.

The overall value model can also be improved through additional iteration. The values and measures presented in this research were based on a review of relevant literature and the researcher's limited HVAC design experience. It was presented to the Air Force Civil Engineering Support Agency (AFCESA) for review, and their inputs were included in the final value model. Continued iterations of the model based on inputs from HVAC design engineers and military decision-makers would further improve the model.

An additional limitation of this model involves the *Aesthetic* measures. Admittedly, the Noise and Visual Impact measures are highly subjective and difficult to score. The impact of Noise, for instance, cannot be fully known until the HVAC system is actually installed. A more objective approach to these measures may be warranted. However, the nature of these measures may not lend themselves to objectivity. For example, even if Noise was measured in decibels, the measure would still be subjective because the perception of loudness varies from one individual to another.

Future Research

Although the results of this research suggest GSHPs are effective for commercial facilities, future research should focus on facilities of varying size and functions. Indeed, chiller/VAV systems and multizone rooftop unit systems are most cost effective for facilities that are larger than the generic facility explored for this research. Other

facilities, such as laboratories or medical facilities should also be studied to evaluate the practicality of GSHPs in buildings that have strict HVAC requirements.

If possible, future research should also be conducted to develop expedient and accurate estimating methods for HVAC systems. Because the validity of the results from the model is dependent on the accuracy of cost estimates and energy consumption estimates, the need for robust estimating methods is apparent. Granted, many of the current estimating methods are already based on sound engineering principles and equations. However, even if the actual method cannot be improved, more user-friendly interfaces and computer-assisted programs could be developed. For systems such as GSHPs, a user-friendly, expedient procedure would be invaluable, and would encourage more HVAC designers to consider their use.

Conclusions

This research has shown that value-focused thinking is an effective decision-analysis methodology for HVAC selection. An objective design tool was developed that can be used to compare the value of different HVAC systems. Further, this research has shown that ground-source heat pumps are viable options for commercial military facilities, regardless of location. They should be considered for all military HVAC projects.

Appendix A. Summary of Measures

Measure: Available Materials

Definition: Are materials and replacement parts readily available in the local area?

SDVF:

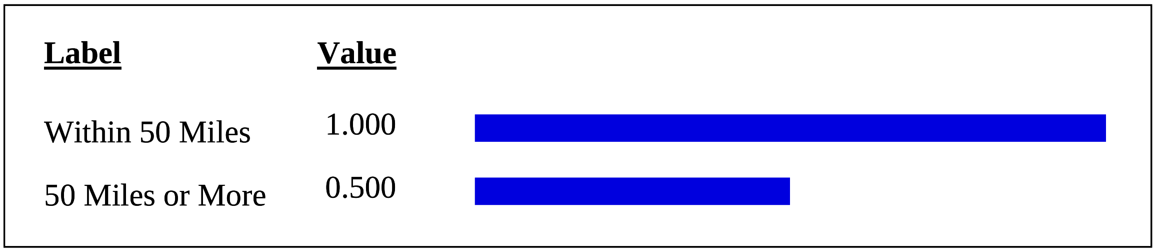


Figure 45. Available Materials SDVF

Category Definitions: Materials are defined as available if they can be obtained on the same business day as required. The local area is defined as within 50 miles of the base.

Comments: None

Measure: Available Service

Definition: Is service readily available in the local area?

SDVF:

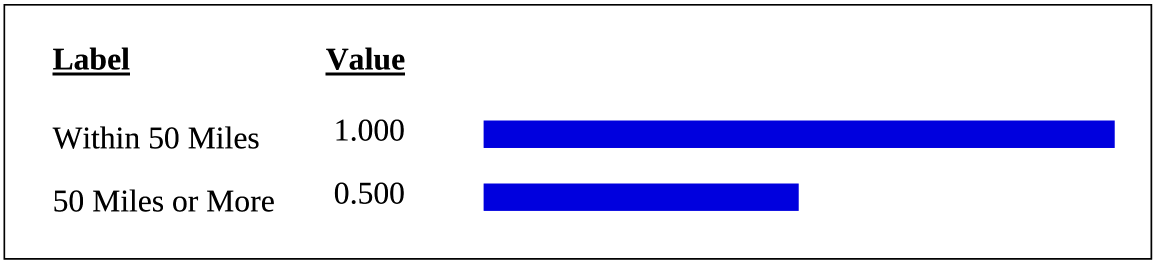


Figure 46. Available Service SDVF

Category Definitions: Service is defined as available if it can be obtained on the same business day as required. The local area is defined as within 50 miles of the base.

Comments: None

Measure: Dehumidification

Definition: How well does the system meet dehumidification requirements?

SDVF:

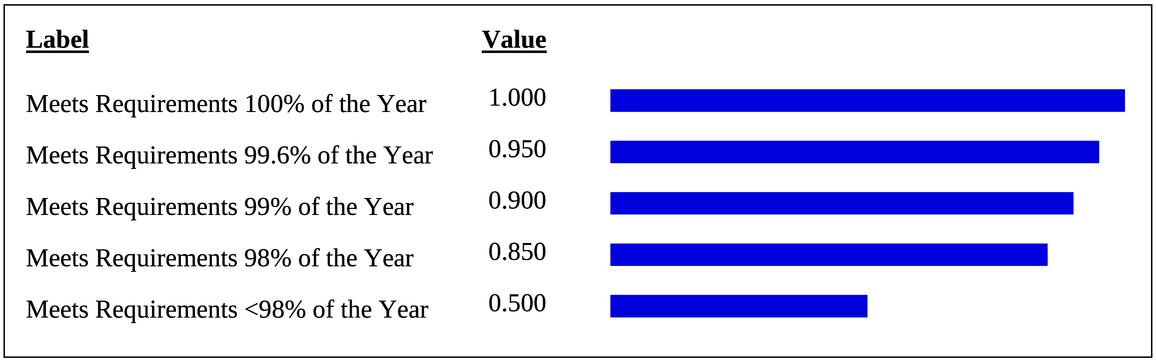


Figure 47. Dehumidification SDVF

Category Definitions: An alternative meets the dehumidification requirements if its latent capacity is greater than the room capacity and its sensible heat ratio is lower than the room requirement (Kavanaugh and Rafferty, 1997).

Comments: When designing HVAC systems, the cooling capacity of the system is determined by the peak cooling load. However, the peak cooling load occurs for only a few hours a year. ASHRAE specifies 0.4%, 1% and 2% design conditions that represent the 35, 88, and 175 hottest hours in the year, respectively. Figure 48 provides an example of the design conditions for Duluth, Minnesota. For Duluth, it experiences a temperature greater than 84F/69F (DB/MWB) for 35 hours of the year. Instead of sizing the cooling system to meet the requirements 100% of the year, HVAC designers often design systems that can meet the cooling requirements at the 0.4%, 1% or 2% design conditions. This

can reduce the required cooling capacity, which results in lower equipment costs. Thus, the categories for this measure reflect the different design conditions that can be utilized.

	0.40%		1%		2%	
Location	DB	MWB	DB	MWB	DB	MWB
Duluth, Minnesota	84	69	81	67	78	65

Figure 48. Example of Cooling and Dehumidification Design Conditions (Johnson, 2000)

Measure: Energy Consumption

Definition: Estimated annual energy consumption; measured in kwh

SDVF:

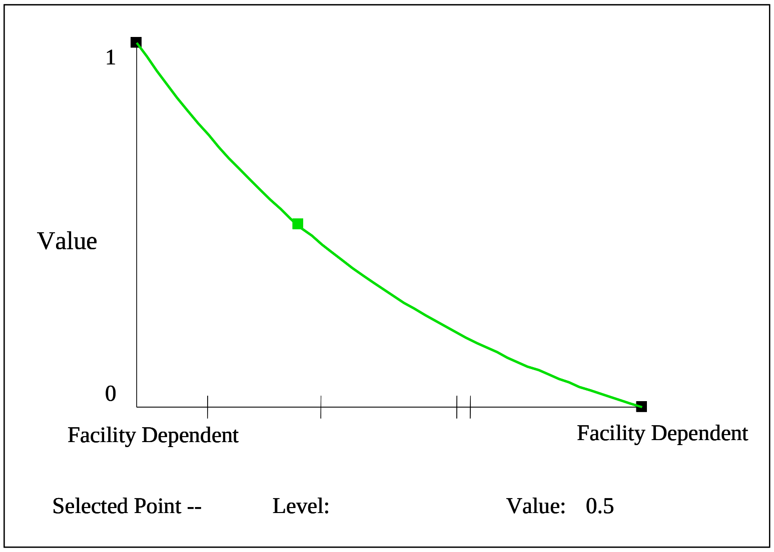


Figure 49. Energy Consumption SDVF

Comments: The upper and lower bounds for this measure are dependent on the facility and location of interest. Based on the range of energy consumption of selected alternatives, the upper and lower bounds may be determined by the highest and lowest levels of energy consumption exhibited by the alternatives. Ultimately, it will be left to the decision-maker to provide upper and lower bounds that best reflect the preferences of the decision-maker.

There are a number of different methods for estimating energy consumption, such as the degree-day method or the bin method (Howell et al., 1998). In addition, a number of different software applications are available, such as DOE-2 or Trace™ 700. For this research, Trace™ 700 was used to estimate energy consumption. The generic facility

described in Chapter 3 was inputted into Trace™ 700, and a specific location was selected. Based on these inputs, Trace™ 700 provided estimates for the energy consumption of all four alternatives considered.

Sources: Trace™ 700

Measure: Initial Cost

Definition: Cost of labor and materials for installation; measured in dollars

SDVF:

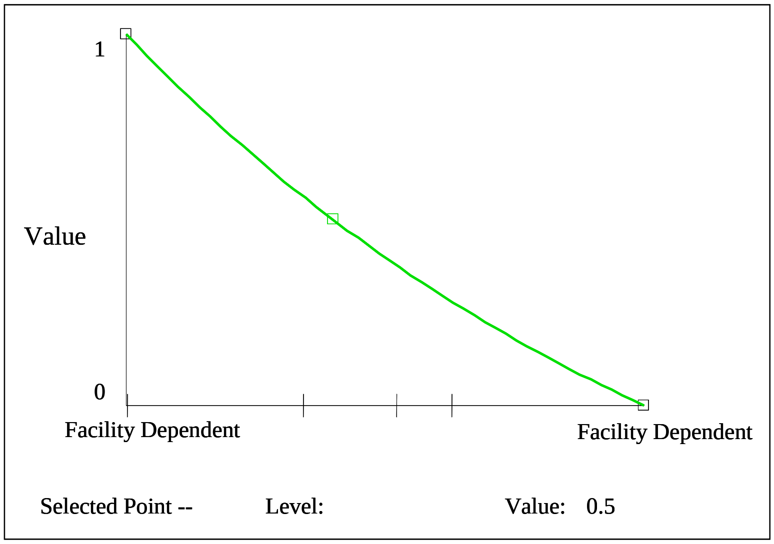


Figure 50. Initial Cost SDVF

Comments: The upper and lower bounds for this measure are dependent on the facility and location of interest. However, it is reasonable to conclude that this measure will exhibit monotonically decreasing behavior as depicted in Figure 50.

To determine initial cost for the conventional HVAC alternatives, the heating and cooling loads must first be calculated. This involves determining the infiltration, ventilation, internal loads (appliances, people, lighting, power, etc), and heat transfer through walls, roofs and floors of the generic office building (Meredith, 1999). This process can be tedious; however, there are a number of software packages that can expedite the process. For this research, Trace™ 700 was used to determine the heating and cooling loads. Once the loads were known, the initial cost estimates were derived

from the *RS Means Mechanical Cost Data* handbook. The initial costs for the rooftop units included costs for the cooling equipment, ductwork, standard controls, and all materials, labor and profit. The initial costs for the chiller/VAV alternative included costs for the chiller unit, distribution piping, cooling tower, cooling tower pumps and piping, and VAV box.

The process of determining the initial cost for the GSHP requires some additional expertise. In addition to the cooling and heating loads, the required length of the ground loop must be calculated for both cooling and heating. The greater of the two lengths determines the required bore. Equations 4 and 5 are used to calculate the require bore for cooling and heating, respectively (Kavanaugh and Rafferty, 1997).

$$L_c = \frac{q_a R_{ga} + (q_{lc} - 3.41W_c)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{4}$$

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41W_h)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{5}$$

where

F_{sc} = short-circuit heat loss factor

L_c = required bore length for cooling (ft)

L_h = required bore length for heating (ft)

PLF_m = part-load factor during design month

q_a = net annual average heat transfer to the ground (BTU/hr)

q_{lc} = building design cooling block load (BTU/hr)

q_{lh} = building design heating block load (BTU/hr)

R_{ga} = effective thermal resistance of the ground, annual pulse (h-ft-F/BTU)

R_{gd} = effective thermal resistance of the ground, daily pulse (h-ft-F/BTU)

R_{gm} = effective thermal resistance of the ground, monthly pulse (h-ft-F/BTU)

R_b = thermal resistance of bore (h-ft-F/BTU)

t_g = undisturbed ground temperature (F)

t_p = temperature penalty for interference of adjacent bores (F)

t_{wi} = liquid temperature at heat pump inlet (F)

t_{wo} = liquid temperature at heat pump outlet (F)

W_c = power input at design cooling load (W)

W_h = power input at design heating load (W)

Once the required bore length was known, the *ASHRAE Ground-Source Heat Pump* design manual and *RS Means* was used to determine the initial cost of the GSHP alternative. The initial cost of the GSHPs included costs for the ground loop, ground-source heat pumps, circulating pumps, and ductwork.

Sources: *RS Means Mechanical Cost Data 2005, ASHRAE Ground-Source Heat Pump* design manual, Trace™ 700

Measure: Location of Equipment

Definition: How accessible is the equipment for maintenance?

SDVF:

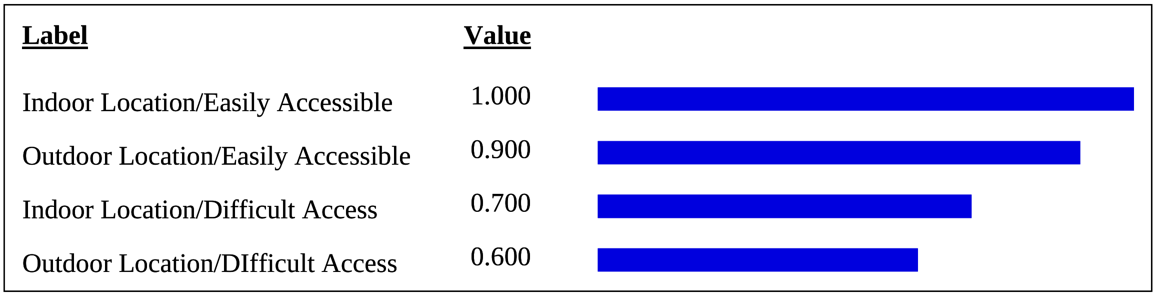


Figure 51. Location of Equipment SDVF

Table 20. Category Definitions for Location of Equipment Measure

Category	Definition
Indoor Location	All equipment that requires routine maintenance is located indoors
Outdoor Location	At least one piece of equipment that requires routine maintenance is located outdoors
Easily Accessible	All equipment that requires routine maintenance is located at ground level
Difficult to Access	At least one piece of equipment that requires routine maintenance is not located at ground level

Comments: None

Measure: Noise

Definition: How perceptible is the equipment noise in the conditioned space?

SDVF:

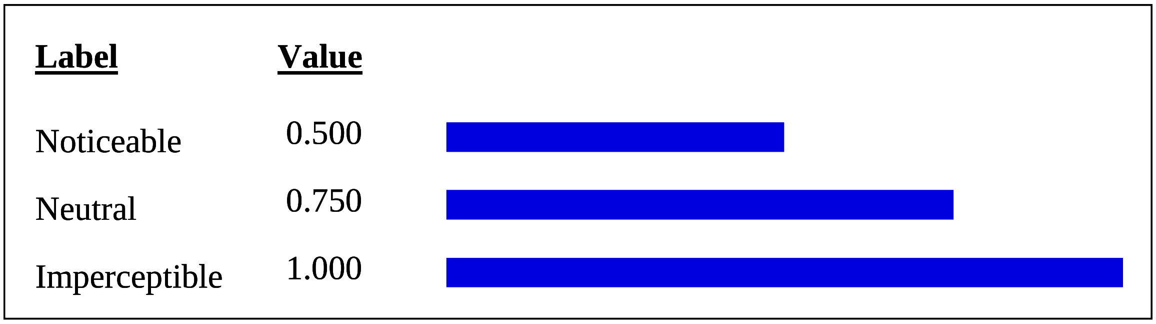


Figure 52. Noise SDVF

Table 21. Category Definitions for Noise Measure

Category	Definition
Noticeable	Noise is perceptible and aggravating to building occupants
Neutral	Noise is perceptible, but unnoticed by building occupants
Imperceptible	Noise is imperceptible in occupied space

Comments: This measure can only be determined by interviewing the building's occupants.

Measure: O&M Cost

Definition: Annual operating costs (based on energy consumption and local utility rates) and annual maintenance costs; measured in dollars

SDVF:

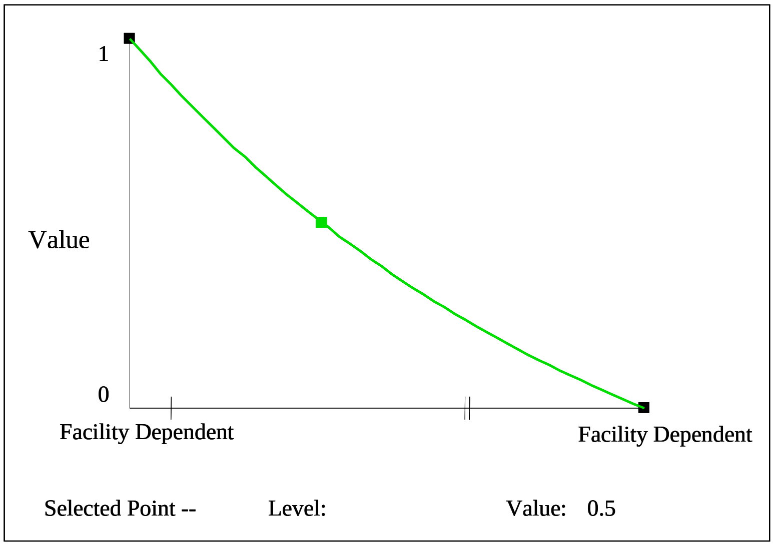


Figure 53. O&M Cost SDVF

Comments: The upper and lower bounds for this measure are dependent on the facility and location of interest. However, it is reasonable to conclude that this measure will exhibit monotonically decreasing preference as depicted in Figure 53.

Based on the projected energy consumption provided by Trace™ 700, the operation cost was determined by multiplying the consumption by the local utility rate at all three locations. The maintenance cost was estimated from ASHRAE RP-929, HVAC Maintenance Costs, which provides estimated maintenance costs for different systems on a cents-per-square-foot scale. For GSHPs, the median maintenance cost based on in-house labor is 8.43 cents per square foot. For the chiller/VAV system, the median cost

for a low-pressure centrifugal chiller was used (35.10 cents per square foot). Rooftop units were not listed in the report. However, the median cost of a packaged air-to-air heat pump (27 cents per square foot) was used to represent the maintenance cost for both rooftop alternatives (Cane and Garnet, 2000).

Sources: Trace™ 700, ASHRAE RP-929, decision-maker input (utility rates)

Measure: Replacement Cost

Definition: Projected replacement cost of components based on 50-year facility life, measured in dollars (brought back to present value)

SDVF:

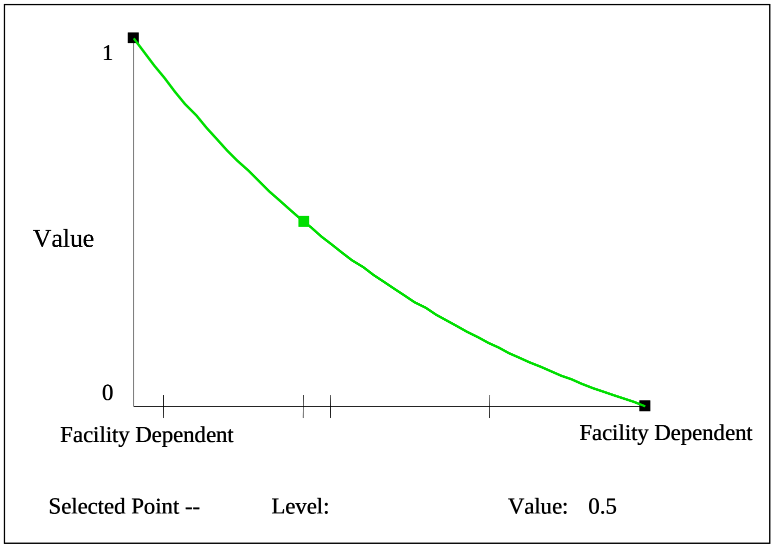


Figure 54. Replacement Cost SDVF

Comments: The upper and lower bounds for this measure are dependent on the facility and location of interest. However, it is reasonable to conclude that this measure will exhibit monotonically decreasing preference as depicted in Figure 54.

The *2003 ASHRAE Applications Handbook* provides estimates for the service life of various HVAC components. Commercial water-to-air heat pumps are projected to last 19 years. Both SZ and MZ rooftop units have a projected life of 15 years. Chillers have a projected life of 20-23 years. Gas-fired furnaces have a projected life of 18 years, while boilers have a projected life of 15-35 years (ASHRAE, 2003). Based on these projected

lifespans, *RS Means* was used to determine the replacement cost of each component. The resulting costs were then brought back to present value using 8% as the discount rate.

The 50 year facility life was selected because it is the median design life expectancy for facilities (Lemer, 1996).

Sources: *2003 ASHRAE Applications Handbook*, *RS Means Mechanical Cost Data 2005*

Measure: Supply Air Temperature (heating)

Definition: How warm is the supply air temperature of the heating system?

SDVF:

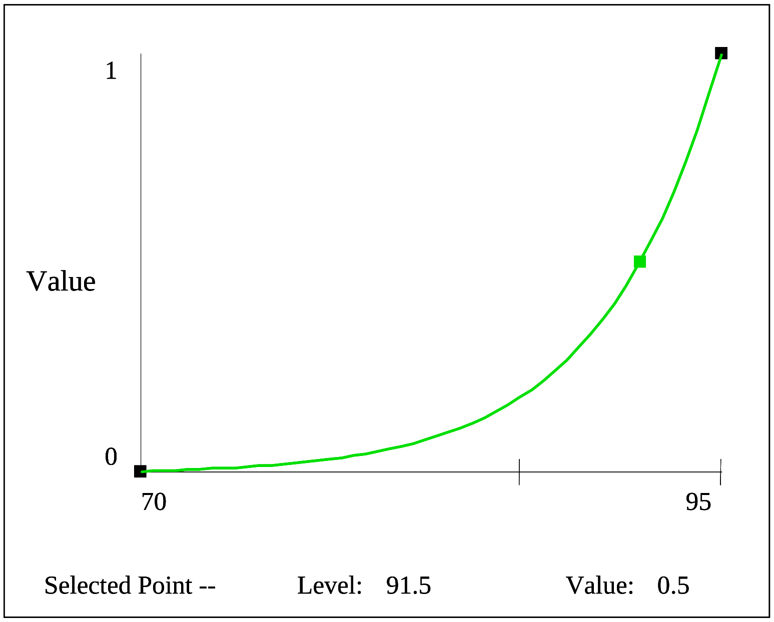


Figure 55. Supply Air Temperature SDVF

Comments: Humans feel comfortable at a skin mean temperature of 91.5F. The range where no discomfort is felt is ±2.5F (Howell et al., 1998). Thus, 95F was selected as the upper bound of this measure. The lower bound was set at typical heating setpoint temperature. Theoretically, a heating system that supplied 70F twenty-four hours a day could maintain a space at 70F.

To estimate the supply air temperature, the mixed temperature entering the heat pump was first calculated. ASHRAE Standard 62-1999 provides the outdoor air requirements for ventilation in commercial facilities. For an office space, the required

outdoor ventilation rate is 20 cfm/person (ASHRAE, 1999). After selecting a suitable GSHP, the approximate mixed air temperature was calculated using Equation 6.

$$t_m = \frac{t_r * Q_r + t_o * Q_o}{Q_m} \tag{6}$$

where

t_m = mixed air temperature (F)

t_r = setpoint temperature (F)

t_o = outdoor design temperature (F)

Q_r = ventilation rate of return air (cfm) = Q_m - Q_o

Q_o = required ventilation rate of outdoor air (cfm)

Q_m = rated ventilation rate of selected GSHP (cfm)

Having calculated the mixed air temperature entering the heat pump, the supply air temperature was approximated using Equation 7.

$$t_s = t_m + \frac{TH}{1.1 * cfm} \tag{7}$$

where

t_s = supply air temperature (F)

TH = heating capacity of the selected GSHP (BTU/hr)

cfm = rated ventilation rate of selected GSHP (cfm)

Sources: *Principles of Heating, Ventilating and Air-Conditioning* (Howell et al., 1998), ASHRAE Standard 62-1999

Measure: Use of Renewable Technology

Definition: Does the HVAC system use renewable technologies?

SDVF:

Label	Value
Renewable Technologies	1.000
No Renewable Technologies	0.000

Figure 56. Use of Renewable Technology SDVF

Table 22. Category Definitions for Use of Renewable Technology Measure

Category	Definition
Renewable Technologies	The system incorporates renewable technologies such that it would qualify for tax credits under EPACT
No Renewable Technologies	The system does not incorporate renewable technologies such that it would qualify for tax credits under EPACT

Comments: None

Measure: Visual Impact

Definition: How obtrusive is the HVAC equipment (e.g. large cooling towers)?

SDVF:

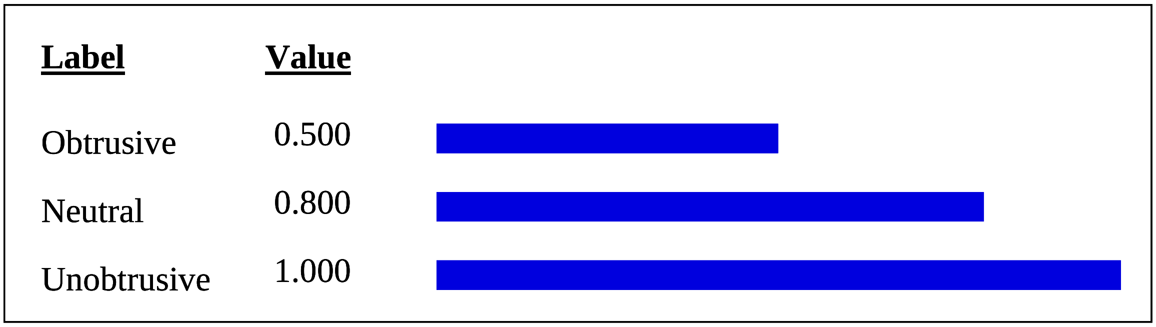


Figure 57. Visual Impact SDVF

Table 23. Category Definitions for Visual Impact Measure

Category	Definition
Obtrusive	Equipment is visually obtrustive to building occupants
Neutral	Equipment is viewable by building occupants, but not considered obtrusive
Unobtrusive	Equipment can not be seen from occupied space

Comments: None

Appendix B. Characteristics of Generic Office Facility

Construction			
Component	Material	U-factor	Notes
Floor	4" LW Concrete	0.213	
Roof	4" LW Concrete	0.213	
Wall	8" LW Block, 1" Ins	0.149	
Glass Type	Double Coated, 1/4"	0.33	Shading Eoeff = 0.56
Wall Height	10 ft		
Plenum	2 ft		
Miscellaneous Loads			
Type	Standard Office Equipment		
Energy	0.5 W/sq ft		
Air Flow			
Ventilation	20 cfm/person		
Internal Loads			
People			
Type	General Office Space		
Density	143 sq ft/person		
Sensible	250 Btu/hr		
Latent	200 Btu/hr		
Lighting			
Type	Recessed fluorescent, not vented, 80% load to space		

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Vita

Captain Jimmy J. Jeoun graduated in May 1996 from Doherty High School, in Colorado Springs, Colorado. He attended Colorado State University in Fort Collins, Colorado and graduated in May 2000 with a Bachelor of Science degree in Mechanical Engineering. He was commissioned through the Air Force Reserve Officer Training Corps at Colorado State University, Detachment 90.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
15-03-2005	**Master's Thesis**	Jun 2004 – Mar 2005

4. TITLE AND SUBTITLE	
USING VALUE-FOCUSED THINKING TO EVALUATE THE PRACTICALITY OF GROUND-SOURCE HEAT PUMPS AT MILITARY INSTALLATIONS	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Jeoun, Jimmy, J., Captain, USAF	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Street, Building 642 WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GEM/ENS/05M-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFCESA/CESM Attn: Mr. Alvin Day 139 Barnes Drive. Suite 1 DSN: 523-6357 Tyndall AFB, FL 32403-5319 e-mail: Alvin.Day@tyndall.af.mil	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Because of potential cost and energy savings, military decision-makers may want to consider the use of energy-efficient heating, ventilating, and air-conditioning (HVAC) systems at their installations. Ground source heat pumps (GSHPs), in particular, show great promise because of their low energy requirements and low life-cycle costs. However, there currently exists no design guidance or established criteria for HVAC selection. Consequently, military decision-makers have no basis for comparing conventional HVAC systems and GSHPs.

The Value-Focused Thinking (VFT) methodology was used to create a multi-objective decision analysis model that measures the value of different HVAC systems. Consisting of five bottom-tier values and twelve measures, the model captures the Air Force's objectives regarding its selection of HVAC systems. Using data collected from three different Air Force bases, the model was used to evaluate four HVAC alternatives (three conventional and one GSHP alternative) at each location. Sensitivity analysis was also conducted to provide additional insight into the HVAC selection process. The results of this research indicate that GSHPs are a viable option and should be considered at military installations. Further, the results prove that the VFT model can be an effective decision analysis tool for HVAC selection.

15. SUBJECT TERMS

Decision Analysis, Value-Focused Thinking, VFT, Ground-Source Heat Pumps, HVAC Selection

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Jeffery D. Weir, Lt Col, USAF (ENS)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3636, ext 4538
U	U	U	UU	130	

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Prescribed by ANSI Std. Z39-18